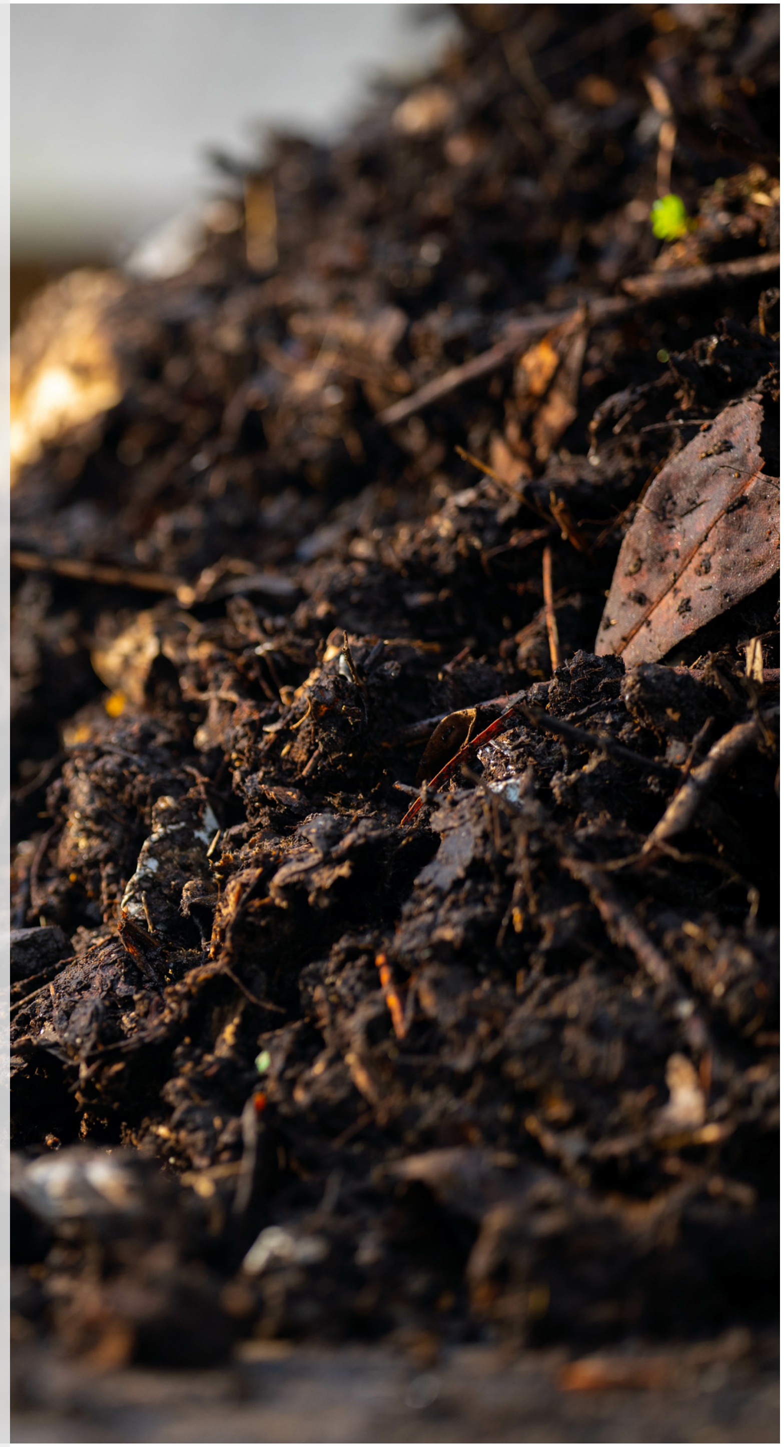
Evaluating Compost Application for Soil Carbon Sequestration on Agricultural Land and Compost Buy-Back Programs in Washington

Report to the Legislature | 2022



WASHINGTON STATE UNIVERSITY
Center for Sustaining Agriculture and Natural Resources

TABLE OF CONTENTS

KEY TERMS

- **Best management practices (BMP's)**: In the context of carbon farming, they are practices that are determined to be effective and practicable (including technological, economic, and institutional considerations) means of increasing sustainability, reducing GHG emissions and generating environmental co-benefits.
- **Carbon farming**: an approach to optimizing carbon capture on working landscapes (particularly agricultural systems) by implementing practices understood to improve the rate at which CO_2 is removed from the atmosphere and stored in plant material and/or soil organic matter (as soil carbon).
- **Carbon dioxide equivalent (CO_2e)**: A metric measure that is used to compare emissions from various greenhouse gases based on their global warming potential (GWP) by converting amounts of other gases to the equivalent amount of CO_2.
- **Carbon to nitrogen ratio (C:N ratio)**: The ratio of soil organic carbon to total nitrogen in soil, plant matter or an amendment.
- **Climate-smart practices (CSP's)**: Agricultural and land management practices that help transform agri-food systems towards being 'greener' and climate-resilient.
- **Conservation districts (CD's)**: Are community-based hubs of natural resource expertise and funding. They're staffed and led by locals who understand the needs of landscapes and fellow community-members that they serve. Each of Washington's 39 counties is represented by at least one conservation district.
- **Conservation practice standards (CPS's)**: Technical guides that serve as the primary scientific references for USDA NRCS. They contain technical information about the conservation of soil, water, air, animals (domestic and wild), and energy resources, while acknowledging related human considerations.
- **Earth system model**: a coupled climate model that explicitly models the movement of carbon through the earth system.
- **Environmental co-benefits**: Co-benefits are the additional outcomes from carbon farming projects that benefit the environment more broadly. E.g.: Improved local water quality, creation of pollinator and fish habitat and cleaner air.

KEY TERMS (cont.)

- **Greenhouse gases (GHG's)**: A gas that absorbs and emits radiant energy within the thermal infrared range, causing the greenhouse effect. The major GHG's of concern for global warming are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and ozone (O_3).
- **Major Land Resource Area (MLRA)**: Land use is used to describe the human use of land. It represents the economic and cultural activities (e.g., agricultural, residential, industrial, mining, and recreational uses) that are practiced at a given place. The Major Land Uses (MLU) series is the longest running, most comprehensive accounting of all major uses of public and private land in the United States.
- **MMRV**: Monitoring, measurement, reporting and verification (of benefits).
- **Natural climate solutions**: Land management activities that conserve and restore native and agricultural lands to reduced GHG emissions and improve soil carbon storage and ecological services.
- **Soil organic matter (SOM) & soil organic carbon (SOC)**: Soil organic matter, of which soil organic carbon (SOC) constitutes about 58%, is the fraction of the soil that consists of plant or animal tissue in various stages of decomposition.
- **Uncertainty (model)**: Model uncertainty has two main sources: the mathematical structure of the model, and the parameterized values within the model which are usually derived from field measurements. Model uncertainty can be constrained by collecting more data in fields of reference to update parameters (like N_2O emissions) that have a high level of uncertainty due to data deficiency.

Photo: Max Belchenko

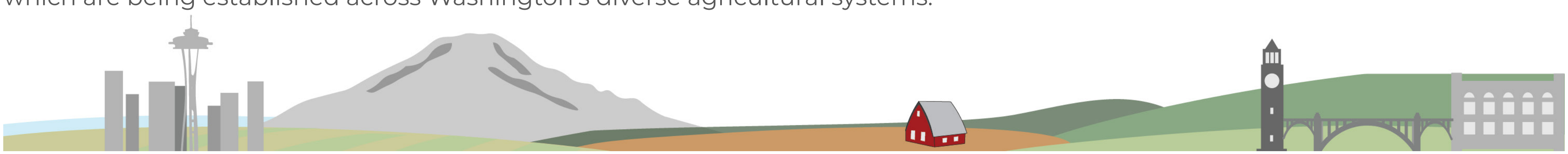
EXECUTIVE SUMMARY

Context and Justification

There has been a large-scale recognition over the last twenty years that organic "wastes" contain valuable nutrients and carbon that can be recovered through composting or other processing and utilized as a soil amendment. Responding to this, a diverse array of organics recovery programs have been developed across Washington and the rest of the country, aimed at diverting organic waste from landfills, including both yard trimmings and in some areas food wastes. A major challenge to the long-term sustainability of these programs in some places has been ensuring adequate demand for the compost produced. While small-scale individual purchases of compost can command a high price, in most cases they are inadequate for absorbing supply generated from municipal scale organic waste collection programs. Among the strategies that have received attention for absorbing supply, attention has been focused on enhancing agricultural and municipal use of compost, as both users have the potential to utilize large quantities of materials. This issue is likely to become more important considering ongoing efforts to increase diversion rates; in 2022, the Washington Legislature passed the Organics Management Law (HB1799, 2022) with a goal of reducing landfill-disposed organic material by 75% compared to 2015 levels, by the year 2030.

One reason for the ongoing interest in increasing recovery and beneficial use of organic waste is that compost and other processed organic wastes can contribute to addressing the climate crisis and other urgent issues facing Washingtonians. In January of 2021, the United States formally returned to the Paris Climate agreement. An unprecedented global commitment to climate action, the agreement requires signatory nations to set forth firm targets to reduce their greenhouse gas (GHG) emissions to limit global warming below 1.5°C. Meanwhile, in 2020, the Washington Legislature enacted statewide greenhouse gas emissions limits, requiring Washington to reduce emissions to 45% below 1990 levels by 2030, 70% below 1990 levels by 2040, and 95% below 1990 levels by 2050. The Climate Commitment Act (CCA) was passed in 2021, establishing the framework for a broad, market-based cap-and-invest program managed by the Washington Department of Ecology. The CCA aims to regulate and reduce carbon dioxide (CO_2) and other GHG emissions toward net zero. Legislative commitments to tackling climate change are instrumental to the health of the planet for future generations and publicly legitimize the need for direct and urgent action in multiple spheres of influence.

Washington's legislative commitment to climate change mitigation is matched by an equally important commitment to sustaining agricultural productivity for future generations. In 2020, the Legislature established the Washington Soil Health Initiative, which designated Washington State University (WSU), Washington Department of Agriculture (WSDA), and Washington Conservation Commission (SCC) to lead research, extension, policy support, technical assistance, and funding opportunities to improve soil health, increase soil carbon sequestration and increase environmental co-benefits of Washington agricultural production systems. Since its launch, the Washington Soil Health Initiative (WaSHI) has selected six sites for a network of long-term agroecological research sites (LTAREs), the first of which was established at WSU's Northwestern Washington Research and Extension Center in Mount Vernon. It also produced the first comprehensive Soil Health Roadmap (2021) and initiated the first State of the Soils Assessment (2022), designed to empirically quantify soil health and its relationship to farm management across WA's diverse cropping systems and climatic regions. The application of organic amendments to agricultural lands is a significant focus of future research at LTARE's which are being established across Washington's diverse agricultural systems.



In 2019, Sustainable Farms and Fields (SFF) was initiated to address agricultural emissions by providing public entities grants for farming practices that increase storage of carbon, decrease GHG emissions, and initiate or expand the use of precision agricultural equipment. SFF was funded at a level of $2M in FY 2023, and among other intentions, will channel funds toward on-farm projects that enhance soil organic carbon storage (carbon farming projects). Among the agricultural practices supported by SFF is the use of soil amendments such as compost, which may be used to increase soil organic carbon (SOC) storage on agricultural lands.

Meanwhile, the Organics Management Law (HB 1799; 2022) while focused on a range of organics management issues, includes elements that support the use of compost on working lands. The Organics Management Law (HB 1799; 2022) , directs the SFF program to fund the "purchase of compost spreading equipment" (section 501), and for the WSDA to establish a "compost reimbursement program" (section 502) which allows farmers to be reimbursed for the purchase of composted materials produced externally to their farms to be applied on their lands, so long as the WSDA can sample soils prior to, and ten years post application. *These additions to HB 1799 indicate a firm legislative commitment to providing opportunities for farmers to economically acquire and utilize compost. Bill additions also demonstrated a commitment to ensuring that scientific entities can quantify the benefits of compost application on agricultural lands into the future.*

Supporting these ongoing efforts, WSU's Center for Sustaining Agriculture and Natural Resources was tasked with a 2021 legislative proviso to prepare a report on two areas relating to compost use. The first task was to develop a model to estimate carbon sequestration from the use of organic waste-derived soil amendments, and to identify current U.S. mechanisms. to provide funding for carbon sequestration from the use of organic waste-derived soil amendments. The second task was to assess local and state government participation, effectiveness, and volume of compost usage within existing compost buy-back programs under RCW 43.19A.120 and 43.19A.130. This report describes findings, knowledge gaps, and policy recommendations for each of the proviso tasks. Note that because model development is more time-consuming than the proviso allowed, and because there are several well-established SOC sequestration models, the team did not on develop an entirely new model. Rather, efforts were focused on calibrating existing model predictions to Washington data and understanding their applicability.

Photo: Doug Collins

Composting for soil organic carbon (SOC) sequestration on agricultural land in Washington

Work on evaluating the role of agriculturally-applied compost was divided into three parts:

1) Review of U.S. Legislative frameworks providing funding for application of organic amendments to agricultural lands.

Literature was reviewed on current U.S. legislative frameworks to provide funding for application of organic amendments to agricultural lands for the purpose of soil carbon sequestration. At present, other than Washington's SSF grants program, there is only one other operational and comparable program in the U.S.: The Healthy Soils Program (HSP) of the California Department of Food and Agriculture. Comparable, insofar as they are funded in perpetuity, supported by legislative funds, and are specifically geared toward soil carbon sequestration. While other states have introduced legislation that specifically mentions 'soil health' and 'soil carbon storage', most have not yet made significant steps toward providing financial incentives for new practice adoption on farm, and even fewer specifically include language around organic amendments. The United States Department of Agriculture's 2022 investment of $3.1 billion via the newly established Climate Smart Commodity Programs will undoubtedly provide incentives for organic amendment use in agriculture along with other climate smart practices; however, the specifics of these programs were not yet available for review.

Given this limitation, this report focuses on comparing the key operational components of the Washington SFF and California HSP programs. Considering the existing legislative instruments available to support carbon farming in Washington, an infographic was produced that suggests a framework for how government agencies, universities and producers might further strengthen collaborations to support carbon farming for climate change mitigation (**Fig 2**).

Key findings from review of U.S. Legislative frameworks providing funding for application of organic amendments to agricultural lands:

- ◊ At present, other than WA's SSF grants program, there is only one other operational and comparable program in the U.S.: The Healthy Soils Program (HSP) of California Department of Food and Agriculture.
- ◊ Existing legislative actions continue to support carbon farming in Washington. An infographic (**Fig 2**) suggests a framework for how government agencies, universities and producers might further strengthen collaborations to support carbon farming for climate change mitigation.

2) Assessment of short- and long-term potential for organic amendments to improve soil organic carbon accumulation and reduce GHG emissions using Washington-specific data and modeling.

After a comprehensive search for available data from historical and current organic amendment studies on agricultural lands in Washington, experimental data was obtained from three studies having *sufficient experimental control and adequate data records, including replicated measurements of soil organic carbon*. Utilizing data from two studies — one in dryland wheat systems and one in irrigated vegetable systems — this effort assessed the potential for organic amendments to improve SOC accumulation and reduce GHG emissions (CO_2, CH_4, N_2O). Results were obtained using two methodologies: measured data from 10 years of production, and simulated data using models into the year 2050. Because the focus of this work was the on-farm benefits of organic amendment applications, emissions/sequestration predictions are only reported from the 'farm gate', and do not include emissions associated with production, transport, or application. Thus, this should not be considered a full life cycle analysis, but rather an in-depth exploration of the ability to enhance soil carbon sequestration in cropland with amendments.

Case study 1, conducted in dryland wheat cropping systems in Davenport, WA, the short-term field data (2016 – 2022) demonstrated the potential for a single high application of compost to stimulate crop growth, even up to five years after initial application. Increased plant growth leads to more carbon being input to the soil over time. Further, the measured data (2016-2022) showed that municipal compost, applied in amounts equal to or greater than > 25,000 kg ha^{-1} (22,304 lb. ac), increased SOC between ~62 – 100% in deeper soil layers (> 60 cm) compared with the synthetically fertilized control. Carbon storage in deeper soil layers is a highly desirable outcome for long-term carbon storage. For drylands, this increase in soil organic carbon may also be important for soil water retention.

Compared with fertilizer use (business-as-usual), the DAYCENT model simulations showed that utilization of 10,000-50,000 kg ha^{-1} (8921 – 44608 lb. ac) compost instead of 'business-as-usual" (fertilizer application) reduced carbon emissions over a 35-year timeframe in wheat-fallow rotations and resulted in a decrease of on farm CO_2e emissions by ~16-60% (excluding emissions associated with compost transport, fuel, and energy). In the wheat-pea-fallow rotation, 10,000-50,000 kg ha^{-1} (8921 – 44608 lb. ac) compost applications improved emissions between ~52-196% compared with fertilizer application over the same timeframe. The greater decrease in emissions between wheat-fallow and wheat-pea-fallow may have been driven by increased nitrogen return to soil from the peas, and less frequent fallowing. *It is important to note that there was no measured field data that allowed validation of N_2O and CH_4 emissions predictions for either case study, therefore this aspect remains unevaluated.*

Photo: Ingo Bartussek– stock.adobe.com

Case study 2, conducted at Puyallup Research and Extension Center, demonstrated that combining a high carbon compost (on-farm mixed compost, C:N ratio 14) with cover crops could increase soil organic carbon to a greater extent than a lower carbon compost (broiler litter, C:N ratio 12) in vegetable cropping systems.

Critically, this trial did not include a 'business-as-usual' baseline in which synthetic fertilizer was used. Therefore, it is not possible to quantify to what extent the studied organic amendments may influence CO_2e emissions compared to the use of inorganic fertilizers. However, despite this limitation, some clear insights were generated relating to carbon dynamics over time. The DAYCENT model simulations suggested that both the high C compost and low C compost types were predicted to lose soil carbon over time. However, between 2003 and 2050 (the modelled period) the high C compost lost ~ 7% less SOC than the on-farm mixed (lower C) amendment. Regarding the ability of the soils to retain carbon added from the amendment, it is possible that soils in this system were nearer to their mineralogical capacity to store organic carbon, resulting in more rapid loss over the long term. The amount of clay in soil is a key determinant of the ability of soils to store SOC in the long term, with the ratio of SOC to Clay being an indicator of total storage capacity [2]. SOC:Clay ratios vary widely between arable systems, but the ratio of SOC:Clay at this site (0.22) was nearer to the higher end of previously reported values [3-5]. Despite this potential limitation to soil carbon retention, it is notable that the on-farm compost, higher in carbon, stimulated cover crop growth to a greater extent than broiler litter, beneficially increasing 'live' carbon inputs from plants to soil over time.

It is important not to over-interpret the results from these two case studies, and to recognize that neither experiment was designed to explore how to maximize carbon sequestration or reduce GHG emissions through the application of organic amendments. Peer-reviewed publications are being developed from these case studies. Concurrently, a third experiment that applied biosolids to Washington dryland wheat systems is being modeled using DAYCENT. A technical report will also be available with further details of the comprehensive methods used for the work that informs this report.

3) Exploration of the suitability of existing modeling tools for quantifying soil organic carbon accumulation and GHG emissions following organic amendment addition in Washington agricultural systems.

Measured data from the two case studies were entered into the two below commonly used models to predict GHG emissions for a 10-year period. The two model estimates were then statistically evaluated and compared.

1. **DAYCENT:** A primarily academically operated, extensively published earth-system model in use by the U.S. National Greenhouse Gas Inventory (the up-to-date version can be obtained from Colorado State University) https://www.nrel.colostate.edu/projects/century/index.php

2. **COMET-Farm:** An online model, partially driven by DAYCENT incorporating a menu-driven graphical interface. The tool was developed by USDA-Colorado State University for the purpose of providing a ranch and farm greenhouse gas accounting system for use by land managers. It uses spatially explicit data on climate (PRISM) and soil conditions (SSURGO) and allows the user to enter detailed information for field, crop, and livestock management, as well as NRCS conservation practice standards (CPS). The model produces GHG emissions and carbon sequestration estimates for the defined situations. https://comet-farm.com/

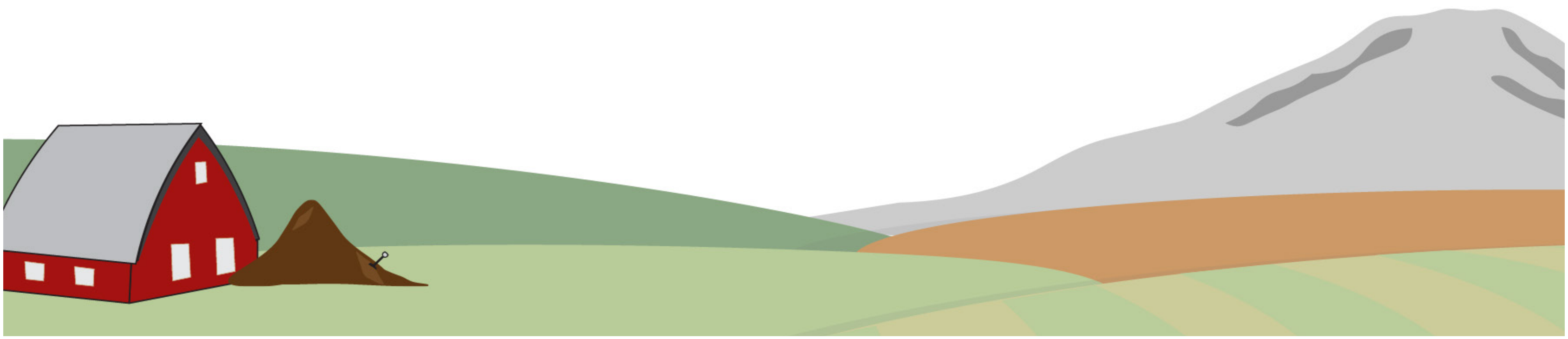
Additionally, one year of GHG predictions was produced from two additional tools. Longer predictions were not possible due to tool limitations, and neither could the predictions be statistically evaluated.

3. **COOL Farm:** Like COMET-Farm, this is an online, menu-driven graphical interface tool that facilitates the calculation of GHG emissions and carbon sequestration under differential farm management and is intended for use by farmers. https://coolfarmtool.org/

4. **WaCSE:** A tool intended for farmers and land managers, developed by the Washington Department of Agriculture using data and parameters from the USDA COMET-PLANNER tool http://comet-planner.com/. Background climate and soil survey data for this tool is obtained from county-rectified major land use resource areas (MLRAs). This tool allows the user to calculate GHG emissions savings (note that this is the change in GHG emissions, in contrast to other tools) when 'business as usual' practices are altered to adopt conservation practice standards (CPS). https://wsda.shinyapps.io/WaCSE/

Our evaluation of the first two tools showed that, compared with DAYCENT the COMET-Farm tool was easier to use, but it had greater bias (deviation of modelled values from measured values) compared with DAYCENT. Model bias for SOC in the dryland case study (Davenport) was ~9% for DAYCENT and ~15% for COMET-Farm, and SOC predictions differed significantly. For the irrigated vegetable case study (Puyallup), model bias for SOC was 3% for DAYCENT and 186% for COMET-Farm. Greater bias using COMET-Farm largely resulted from errors in the background SOC data used to initialize the model. For example, COMET-Farm model significantly overestimated the initial SOC content of the Puyallup soil by ~4%. Therefore, caution should be exercised in accepting the emissions predictions from COMET-Farm for this study.

For the dryland case study (Davenport), N_2O emissions estimates between the two models differed by ~50%; DAYCENT predicting higher N_2O emissions. It is important to remember that on-farm N_2O emissions were not able to be verified using experimental data, therefore the accuracy of predicted emissions and SOC sequestration for each dataset is assumed based on their ability to approximate measured SOC values, and it is accepted that this is not a complete assessment of model performance.



Between the four models, GHG emissions (positive value) and sequestration (negative value) estimates between application of 50,000 kg ha^{-1} compost and 'business as usual' (synthetic fertilizer application) in the dryland wheat system varied between + 0.003 T ha^{-1} yr^{-1} (WaCSE) and – 0.03 T ha^{-1} yr^{-1} (DAYCENT). In the Puyallup vegetable system, GHG estimates between the broiler litter and on-farm mixed compost amendments using the Cool Farm and WaCSE tools (being similar) varied between 0.08 T ha^{-1} yr^{-1} and 0.18 T ha^{-1} yr^{-1}. For COMET-Farm, these estimates were -1.70 T ha^{-1} yr^{-1} for the on-farm mixed compost, and -8.63 T ha^{-1} yr^{-1}.

The tested model tools can be broadly defined as those that offer increased site-level accuracy, but which require large amounts of data and operational expertise, versus those that require minimal data and a low-level of user skill but for which there is a trade-off for reduced accuracy and increased uncertainty at the site-scale. Taken together, results suggest that model users will need to carefully consider several important questions when deciding whether there is a model suitable for calculating GHG emissions impacts from carbon farming. These questions include:

1) What data is available, and what resources are available for collecting additional on-farm data?
2) What is the skill level of the user(s)?
3) Given that models have differing data requirements which influence accuracy, what level of uncertainty is acceptable? For example, more uncertainty may be acceptable for a county level assessment concerned only with overall directional GHG impacts, compared to a field-specific assessment.
4) If a high uncertainty is not acceptable, what resources are available to utilize more complex models, and to collect the needed data for model parameterization?

Key findings from exploration of the suitability of existing modeling tools for quantifying soil organic carbon accumulation and GHG emissions following organic amendment addition in Washington agricultural systems:

- ◊ Our evaluation of the first two tools showed that, compared with DAYCENT the COMET-Farm tool was easier to use but had increased bias (deviation of modelled values from measured values). For Case Study 2, biases from COMET-Farm were ~186%. This level of bias is high enough to warrant caution in accepting the GHG emissions predictions.
- ◊ It is important to note that all both simple and complex models contain a measure of uncertainty, some of which is quantifiable and some of which is not. Model uncertainty can typically be minimized via incorporation of greater amounts of field data, collected in varied systems. This is one important reason for continued long-term research on organic amendment applications to Washington's diverse agricultural systems.
- ◊ For models that require low amounts of input data, increased bias and therefore uncertainty may be a trade-off for ease-of-use. Online tools are useful for rapid estimates of GHG emissions reduction potential in the short-term and may be more relevant when applied over larger areas or groups of farms. Users should be cautious in relying on these tools for site-specific estimates. When used in isolation, tools may not be suitable to establish priority funding for carbon farming initiatives.

Assessment of government compost usage

To assess government compost usage, approximately 300 cities, towns, and counties in Washington were contacted with an online survey on compost procurement. Sixty responses were received, resulting in a 20% response rate. Based on the responses, it was possible to characterize four general typologies that can be useful for making sense of the substantial diversity that exists across local governments in Washington.

- **Type 1:** Does not use compost because the city is small and does not have parks or capital projects. Examples: Index, Coulee Dam.
- **Type 2:** Does not use compost because compost is not sold nearby. Examples: Pateros, Colville.
- **Type 3:** Uses compost because they have a processing operation (Wastewater Treatment Program or self-haul yard waste). Examples: Centralia, Lynden.
- **Type 4:** Uses compost because they are a larger city with many projects purchasing from outside composting facilities. Examples: Kennewick, Kirkland.

Among our respondents, 70% reported that they never use compost, and therefore fall in Types 1 or 2. More respondents were Type 1, with the two Type 2 entities both located in Northeast Washington. Some respondents also said that compost was not an approved material for potential use.

Among those who used compost, most use very little, or could not estimate usage. Among those who could estimate compost volume applied, the most frequent response was 20 cubic yards or less, at a cost of less than $1000. Parks and public works directors often knew that they use compost but could not report the volume used or dollar value spent. Treasurers tend not to know because the cost is so low.

What became clear was that systems were not in place in most municipalities to document compost use – either through a buy-back program, or from other sources, whether the use was directly by the municipality or indirect, such as via a contract for a larger project. The lack of readily available quantitative information made it infeasible to create a reliable database of municipal compost use at this time. Therefore, an important outcome of this report was the finding that documenting use could be challenging for many towns and cities. Developing flexible administrative systems for tracking municipal compost procurement, that work for very small to large cities will be a challenge, but successfully overcoming this could reap rewards by generating quantitative information and better insights about what strategies are working across Washington, and how to improve municipal compost use over time.

Photo: Nicole Kandi - stock.adobe.com

Based on the paucity of quantitative information, efforts were put towards in-depth discussions with a mix of small, medium, and large towns and cities across Washington to better understand representative experiences, and the perceptions of obstacles to increased municipal compost use. Small towns and cities included Port Angeles, Port Townsend, and Westport. Large cities were Seattle, Spokane, and Tacoma. Discussions were also conducted with Pierce and Stevens County.

Key themes that emerged from these discussions included the fact that there are successful models of compost production and use at a variety of scales of communities across Washington. Among small cities with successful composting programs, there are examples where demand exceed supply, in which case requirements for municipal buy-back may crowd out private demand. In contrast, for larger local government entities, supply is much greater, and municipal demand is not in danger of crowding out private demand.

While discussions were wide ranging, there were some common themes in terms of perceived obstacles to expanding municipal compost procurement. It is important to note that it was beyond the scope of this report to determine whether or not perceived obstacles were real or not. However, it is also the case that perceptions alone can be an obstacle, indicating a need for improved communication if they are based on flawed information.

Reducing contamination was the most often mentioned limitation to expanded municipal compost use. This is not surprising in that it is often mentioned as the primary concern for other compost uses such as within agriculture. Reducing contamination during compost production can be costly, leading many of our respondents to focus on the need for reducing contamination prior to materials entering a composting facility, via materials standards and other strategies.

Inconsistency in municipal demand for compost, often paired with insufficient storage space, was also highlighted as a challenge to increasing municipal compost procurement particularly for small- and medium-sized cities. Their perspective is that compost use is tied to specific capital projects, like parks and roads, that are sporadic over time, and do not match the more regular patterns of organic waste and compost generation.

Funding was also cited as a major limitation for many municipalities. Needs for funding ranged from salaries for workers to larger facilities for storage or compost curing.

Photo: kamonrat- stock.adobe.com

Key findings of assessment of government compost usage

- ◊ Meeting the goals of HB 1799 will require improvements in administrative systems for tracking use and overcoming obstacles to using compost for various applications.

- ◊ Most municipalities contacted had very little information readily available on their current and past compost use, whether via buy-back programs, direct use of other compost, or indirect use (such as via a contractor). Documenting use is likely to be somewhat less of a problem for large cities like Tacoma, Seattle, and Spokane. Smaller and medium-sized cities should consider the development of a common system that all can use. Although documenting quantities of compost used by towns, cities, and counties is perceived to require significant additional effort, overcoming this obstacle could lead to improved insights over time about what strategies are working most effectively to encourage local government compost use, and what barriers need to be addressed.

- ◊ Most local governments do not purchase compost. Most of these entities are small and do not have parks or capital projects, while a few are in areas of the state where compost is not available nearby.

- ◊ Contamination with non-compostable items in finished compost, was the most frequently mentioned obstacle to greater municipal use of compost.

- ◊ City size is also an important consideration in overcoming obstacles to increased municipal compost use. For example, inconsistency in municipal compost demand is a significant issue for smaller cities but is likely to be less of a problem for large cities. For smaller cities, challenges in producing more compost (and in some cases use by the public) tend to limit higher governmental procurement.

Part 1:

Composting for Soil Carbon Sequestration on Agricultural Land in Washington

OVERVIEW

Managing croplands to increase soil organic carbon (SOC) can be an important strategy for improving soil health under intensive agricultural production. Soil organic carbon regulates nutrient availability for crops, increases soil water holding capacity, and promotes soil structure to reduce erosion and runoff [6-8].

From a climate perspective, SOC development is critical. Soil organic carbon represents 25% of the potential for natural climate solutions to mitigate climate change (23.8Gt $CO_2e\ yr^{-1}$) and 47% of the mitigation potential in agricultural systems dependent on SOC accumulation [9, 10]. While farms are usually a source of carbon emissions, when managed properly, they can act as a carbon sink.

Accordingly, there has been great interest in SOC on agricultural lands because farmlands have the capacity through some simple changes in management practices (i.e.: reducing tillage) to sequester atmospheric CO_2 in plants and soil.

Alternate management techniques like cover cropping, organic amendment addition, and reduced tillage can increase SOC sequestration, with individual practices having capacity within the magnitude of 2-5 Pg C yr^{-1} globally [1]. However, despite this potential, uptake of some sustainable practices in Washington remains low, particularly in some regions. Barriers include water constraints, economic costs, limited access to organic amendment resources in some areas, and soil compaction which necessitates tillage.

Meanwhile, compost programs have continued to grow across the state, diverting increasing amounts of organic wastes from the landfill. These "wastes" contain carbon and plant nutrients (N, P, K and micro-nutrients) that can be an important input to sustain agricultural soils, especially in parts of the state where other options for increasing carbon inputs are limited.

In the rainfed, wheat-dominated production systems of the Columbia Plateau and Palouse regions of eastern Washington, carbon inputs from crop biomass are low, and it has been difficult to build SOC over time largely due to soil degradation and erosion [11]. Some innovative producers are working to incorporate cover crops, but this has been challenging due to water limitations in these areas. Given water constraints, it is therefore possible that organic amendments may be one of the limited options to increase carbon inputs in drylands.

Comparatively, in irrigated row cropping systems, cover cropping is a more secure option to increase soil C sequestration given plentiful water resources. Organic amendments including compost are also more widely used in these areas, especially because many of these systems are in closer proximity to compost production.

Part 1 of the report contains three sections that explore the potential for compost to be used on agricultural lands for soil carbon sequestration. **Section 1** summarizes literature on U.S. legislative frameworks that provide/will provide funding for application of organic amendments to agricultural lands for the purpose of soil carbon sequestration. **Section 2** presents and models experimental data from two organic amendment studies in Washington: one in dryland wheat, and one in temperate row cropping. **Section 3** compares available model tools to estimate soil carbon sequestration in Washington agricultural lands using Washington data.

Photo: Katie Doonan

SECTION 1.

REVIEW OF U.S. LEGISLATIVE FRAMEWORKS FOR PROVIDING FUNDING FOR APPLICATION OF ORGANIC AMENDMENTS TO AGRICULTURAL LANDS

Most U.S. programs to reduce GHG emissions do not funnel funds toward 'green spending'

Currently, all the west coast (California, Washington, and Oregon), and several states on the Eastern seaboard (the RGGI states; Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Vermont, and Virginia) have implemented some form of declining cap on greenhouse gas emissions towards achieving a net-zero target by 2050. Others have extended this system further, developing 'cap-and-trade' or 'cap-and-invest' programs which aim not only to control total emissions, but generate funds from the sale and trade of compliance instruments (California and Washington, RGGI). Cap-and-trade programs cover the emissions intensive transport, fuel, and energy sectors and require that companies remain within an emissions allowance, or purchase GHG emissions permits annually at auction. The funds generated from these auctions go towards improving technologies and infrastructure to further reduce GHG emissions.

With most of these programs still in their infancy, only one program, the California Cap-and-Trade, appropriates funds from the sale of compliance instruments for the express purpose of improving soil health on agricultural lands, specifically including the application of organic amendments as a funded practice. Others, like Washington, while not yet appropriating funds from cap-and-invest, have well-developed base frameworks that generate funding for on-farm programs and demonstration projects.

Meanwhile, many U.S. states have passed legislation in some form that mentions "soil health" and include a focus on improving agricultural management to increase soil carbon sequestration, however, very few of these programs have ongoing funding or adequate structure. Washington is noteworthy both for its ongoing funding commitment to soil health, and for the high degree of integration between government agencies and conservation districts who on the one hand facilitate technical support and on-farm monitoring and verification, and land-grant universities who on the other hand carry out large-scale research projects generating data and educational resources. In short, there is a high potential for Washington to continue to lead the country in supporting soil health in agricultural lands, within which there may be opportunities to better manage the application of organic amendments to agricultural lands to improve soil carbon sequestration, reduce reliance on synthetic fertilizers, and mitigate GHG emissions.

Photo: Africa Studio

Key operational components of the California Healthy Soils and Washington Sustainable Farms and Fields programs

Of the U.S. states that have passed legislation to protect the health of their soils, California, via the Healthy Soils Program, and Washington, via Sustainable Farms and Fields, have developed incentive programs, funded in perpetuity, that are specifically geared toward increasing soil organic carbon and reducing greenhouse gas emissions through changes in agricultural management practices. While differing slightly in their operational components, the programs have common overarching goals. The California Healthy Soils Program "provides financial assistance for the implementation of conservation management that improves soil health, sequesters carbon and reduces greenhouse gas emissions", and the Washington Sustainable Farms and Fields program "addresses emissions by creating a grant program to incentivize farmers to adopt practices designed to sequester carbon or reduce emissions". While both programs provide incentive payments for climate-smart practices, they differ regarding to whom the funds are supplied, how the projects are defined and administrated, and to what level and by whom technical assistance is provided (**Fig 1**).

Within each of the programs, emissions reduction and soil carbon sequestration are achieved through the implementation of conservation practices (**Table 1**), many of which have conservation practices standards (CPS's) which contain "detailed technical information about the conservation of soil, water, air and related plant and animal resources" for climate-smart practices (CSP's). These CSPs are approved by the U.S. Department of Agriculture Natural Resource Conservation Service (USDA NRCS) as those which contribute to greenhouse gas emission reduction and carbon sequestration. Current NRCS conservation practice standards can be found here: https://www.nrcs.usda.gov/resources/guides-and-instructions/conservation-practice-standards

For these two programs, eligible agricultural conservation/best management practices are divided into categories. For the HSP, categories are defined by agricultural type: cropland, orchard or vineyard, and grazing land. For the SFF, categories are defined as follows: agroforestry, grazing and pasture, livestock partnership, soil health, and nitrogen management (**Table 1**). In some cases, practices approved for grant funding through the California HSP and Washington SSF programs do not yet have associated CPS's, however CPS's are in constant development as scientific research progresses and best management practices (BMP's) are determined. Each program may approve additional practices as additions are made to the approved list of climate-smart practices or to match state-specific requirements. At present, the most significant addition to practice standards and most relevant to this proviso is the recently codified (Nov 2022) CPS 336 "Soil Carbon Amendment" which sets out standards for the use of, among other soil amendments, compost, for "all land uses where organic carbon amendment applications will improve soil conditions with the exception of native grasslands or fallow land". The standard provides guidance to states as to the use of organic amendments on agricultural land and allows compost application to become an accepted practice within USDA incentive programs.

Photo: Vaceslav Romanov

Table 1: Conservation practices and standards approved for funding through the California Healthy Soils and the Washington Sustainable Farms and Fields Programs. Note: Some practices that are included in the Washington SSF program (i.e.: Anaerobic digestion and alternative manure management) while not included in the California HSP are incentivized by other programs.

Conservation Practice	Standard No.	HSP Category	SFF Category
Alley cropping	CPS 311	Cropland	Agroforestry
Anaerobic digester	CPS 311	NA	Livestock partnership
Compost application	CPS 336	Cropland, Orchard, Grazing	Soil Health
Conservation cover	CPS 327	Cropland, Orchard	Soil health
Conservation crop rotation	CPS 328	Cropland	Soil Health
Contour buffer strips	CPS 332	Cropland	Soil Health
Cover crop	CPS 340	Cropland, Orchard	Soil Health
Feed management	CPS 592	NA	Livestock partnership
Field border	CPS 386	Cropland	Soil Health
Filter strip	CPS 393	Cropland, Orchard	Soil Health
Forage and biomass planting	CPS 512	Cropland	Soil Health
Grassed waterway	CPS 412	Cropland	Soil Health
Hedgerow planting	CPS 422	Cropland, Orchard, Grazing	Agroforestry
Herbaceous wind barrier	CPS 603	Cropland	Soil Health
Mulching	CPS 484	Cropland, Orchard	Soil Health
Multi-story cropping	CPS 379	Cropland	Agroforestry
Nutrient management	CPS 590	Cropland, Orchard	Nitrogen Management
Prescribed grazing	CPS 528	Grazing	Grazing and pasture
Range planting	CPS 550	Grazing	Grazing and pasture
Residue and tillage management–no-till	CPS 329	Cropland, Orchard	Soil Health
Residue and tillage management–reduced till	CPS 345	Cropland, Orchard	Soil Health
Riparian forest buffer	CPS 391	Cropland, Grazing	Agroforestry
Riparian herbaceous cover	CPS 390	Cropland	Agroforestry
Roofs and covers	CPS 367	NA	Livestock partnership
Silvopasture	CPS 381	Grazing	Agroforestry
Strip cropping	CPS 585	Cropland	Soil Health
Tree/shrub establishment	CPS 612	Cropland, Grazing	Agroforestry
Vegetative barriers	CPS 601	Cropland	Soil Health
Waste separation facility	CPS 632	NA	Livestock partnership
Whole orchard recycling	CPS 336	Orchard	NA
Windbreak/shelterbelt establishment	CPS 380	Orchard, Grazing	Agroforestry

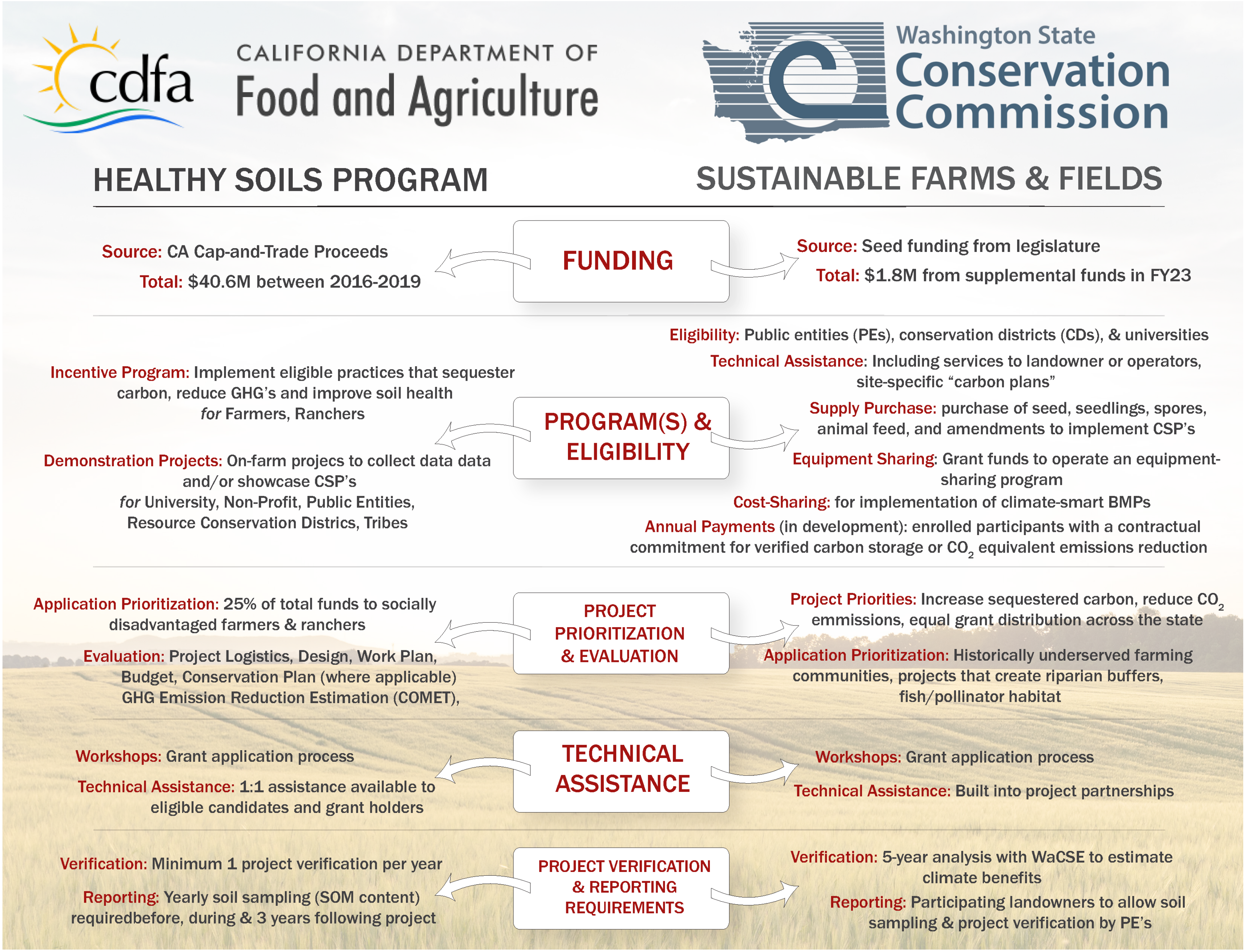


Figure 1: Comparing key operational components of the CA HSP and WA SFF Programs

Existing opportunities for incentivized use of organic amendments for soil health improvement and carbon sequestration in Washington

Recycling organic waste is a key goal of WA's 2021 State Solid and Hazardous Waste Plan [12]. Organic materials – food waste, yard and garden waste and manure – are the greatest contributors to the waste disposal stream in Washington [13]. In 2022, Washington Legislature passed House Bill 1799 (HB 1799) "Organics Management Law" which, in a bid to reduce landfill-disposed organic material by 75% compared to 2015, requires state and local governments, businesses, and other organizations to reduce the amount of organic materials disposed in landfills and to divert these to organics management facilities. It is expected that the passing of this legislation will increase the demand for processed organic materials like compost.

Organic food waste and manure being delivered to an organics management facility

Photo: Doug Collins

In anticipation of an increase in compost products becoming available because of the enacted legislation, the bill added new language under the cost-share funding category of the Sustainable Farms and Fields program. This language allows the program to fund "purchase of compost spreading equipment, or financial assistance to farmers to purchase compost spreading equipment, for the annual use for at least three years of volumes of compost determined by the commission to be significant from materials composted at a site that is not owned or operated by the farmer" as well as "...the purchase or lease of digestate spreading equipment". In addition, the SFF is directed to fund "scientific studies to evaluate and quantify the greenhouse gas emissions avoided as a result of using crop residues as a biofuel feedstock or to identify management practices that increase the greenhouse gas emissions avoided as a result of using crop residues as a biofuel feedstock" and to fund "efforts to support the farm use of anaerobic digester digestate, including scientific studies, education, and outreach to farmers". As well, there is the potential for compost products to be acquired under the 'purchase of supplies' category of the SFF which mentions 'soil amendments". Further, the NRCS recently completed review and alteration of CPS 336 "Soil carbon amendment" which directs the application of "amendments derived from plant or animal residues to improve the physical, chemical, and biological properties of the soil" and designates compost as one such amendment for this purpose. In summary, there are a multitude of legislative instruments and effective use protocols already in place to support the increased application of organic amendments to agricultural land in Washington.

Proposed framework for successful carbon farming initiatives in Washington

Carbon farming, the concept of improving soil health to increase soil carbon sequestration and reduce GHG emissions has mobilized government agencies, researchers, farmers, non-profit organizations, and the private sector because of the possibility that differential management of agricultural lands could significantly contribute to mitigating the anthropogenic impacts of climate change. Here we focus on the interplay between public sector entities (specifically, universities, government agencies, and legislators) and growers in development of carbon farming initiatives.

To maximize the benefit to the environment, a collaborative approach to informing policymaking, driven by science-based programs developed in partnership with technically-equipped government agencies and land-grant universities having the tools and resources to support the custodians of agricultural lands (growers and farmers) is required. For researchers and resource management agencies, this implies responsibility for open, needs-based inquiry, rigorous analyses, and commitment to the wide dissemination of research and programmatic results to the Legislature and the public. For the public and private entities that receive and disseminate funding, there is a commitment to the responsible conduct of research, an obligation to social justice and equity, and importantly, the assurance that program results will be accurately reported to certify that public funds continue to be directed where they are most impactful.

Globally, agriculture is one of the industries most likely to be affected by the negative impacts of climate change, and Washington agriculture is no exception. Impacts that will need to be managed include the potential for worsening droughts and heat stress in the eastern drylands and central region on one hand, and unprecedented rainfall and flooding in the western regions on the other. Farmers will need coordinated efforts now more than ever, so they can access the tools, funds and resources needed to sustainably increase their yields, improve resilience to extreme weather, and increase the health of their soils toward climate change mitigation.

The following infographic (**Fig. 3**) is a suggested framework by which government, land-grant universities and producers might collaborate on, and in turn mutually benefit from developing and supporting climate-smart agriculture initiatives toward net-zero goals. Many of these components are already underway in Washington . Further, while carbon market participation is outside the scope of this proviso, agricultural carbon markets are important and rapidly developing, and from a grower perspective could significantly increase farmer/producer fiscal benefits from adopting climate-smart practices. Not all practices may be creditable within a market framework, but for those practices that are included, additional practice uptake could be incentivized.

Legislators specify the policy framework under which industries will reduce emissions *via* cap-and-invest programs, a portion of the funds from which could be invested to facilitate additional reductions via 'green spending'. Concurrently, there is a growing need to clarify gaps in the available science which **universities** can address. From these funding streams, **government agencies and conservation districts** are enabled to provide incentive payments, technical support, and monitoring and verification services to **farmers**, while **universities** invest in long-term research, data generation and extension services. Further, **university** services can support future policy development and increase farmer engagement through education and outreach. With the support of state funds, technical assistance from **universities, government agencies, and conservation districts, farmers** can be prepared to implement changes and have the skills and support to monitor and verify the climate benefits of management changes on their land so their efforts can be accurately quantified and counted toward net-zero goals.

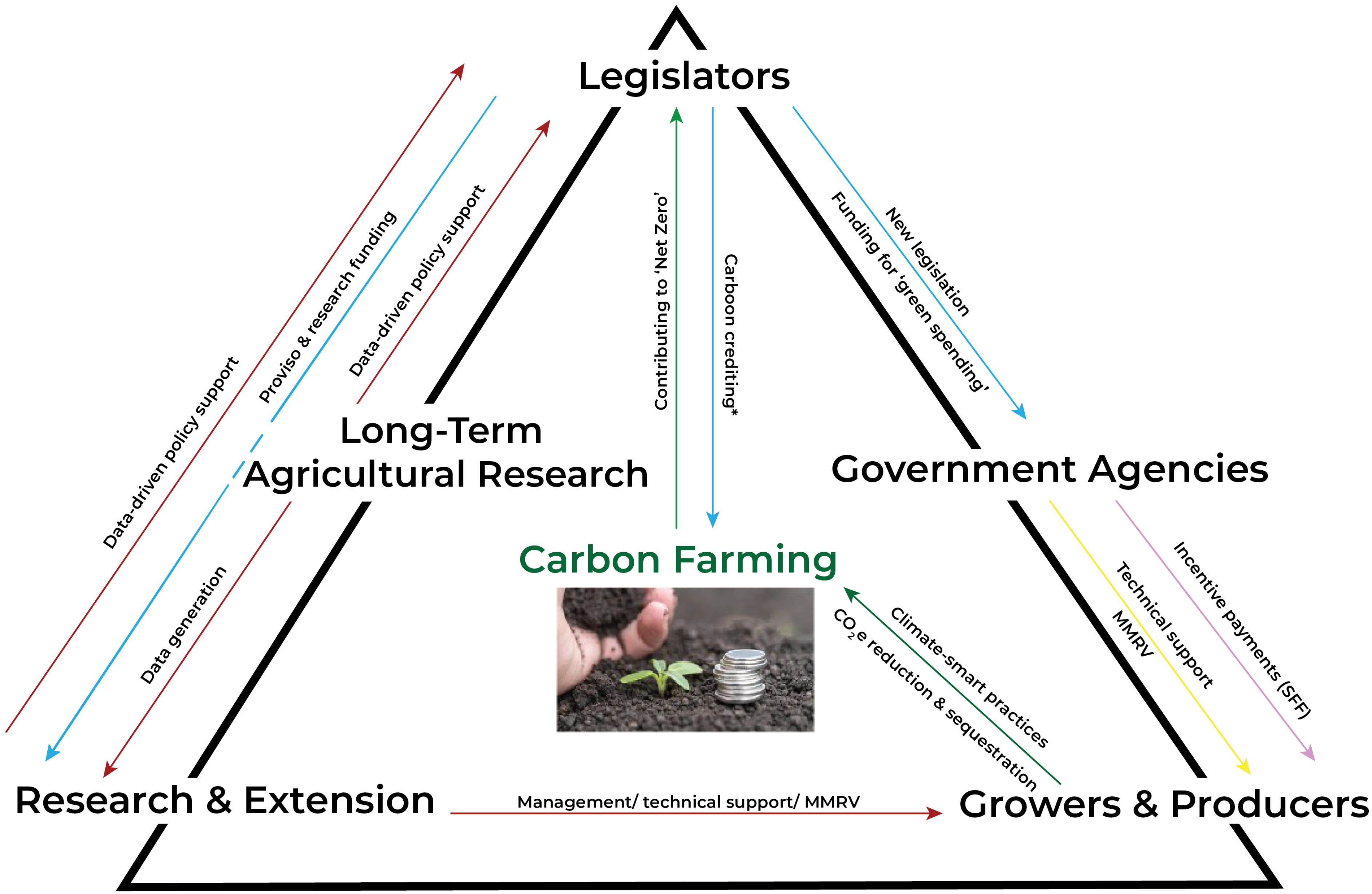


Figure 2: A Washington framework for multi-stakeholder collaboration on carbon farming initiatives.

SECTION 2.
ASSESSMENT OF SHORT- AND LONG-TERM IMPACTS OF ORGANIC AMENDMENTS USING WASHINGTON-SPECIFIC DATA AND MODELING

Organic amendment case study 1: Wilke Farm Dryland Wheat (Davenport)

An organic amendment being field applied

Photo: Chesapeake Bay Program, CC BY 2.0

A dryland wheat crop prior to harvest

Photo: Sara Tm - stock.adobe.com

Site description: A long-term compost study site was established at the Washington State University Wilke Research Farm in Davenport, Washington in 2016. The no-tillage, non-irrigated dryland wheat field site is situated on silt loam soil with an average of 337 mm of precipitation annually, and experiences extensive dry periods.

Experimental treatments: In September 2016, municipal compost, obtained from Barr-Tech (Sprague, WA) was surface applied at one-time rates of 10,000, 25,000, and 50,000 kg ha^{-1} (8,921, 22,304, 44,608 lb. ac.) dry weight basis, compared against a conventionally fertilized control, fertilized annually (11.2 g N per m^2 as 46-0-0-0, 3.36 g P per m^2 as 16-20-0-13) and a control that received neither compost nor fertilizer. The compost, a mixture of yard and lawn trimmings, recyclable food materials and municipal biosolids, had a carbon to nitrogen ratio of 15, added 270, 675 and 1350 g m^2 of organic C to the system respectively. The compost treatments did not receive fertilizer. Two crop rotations were managed within each treatment: winter wheat-fallow (WF), and winter wheat – fallow – winter pea – fallow (WWPF) for a total of 4 replicates of each rotation and compost treatment. Crops were planted in September of each year and harvested in July of the following. Full experimental results from this study are in the process of being analyzed and prepared for peer review publications.

Sampling: Crops were harvested annually, grain yields quantified, and soil samples to 15, 30, 60 and 90 cm taken concurrently. Soils were analyzed for soil organic carbon and nitrogen, and other nutrients.

Statistical analysis and GHG modelling: Compost application rate and crop rotation influences on crop yields and soil organic carbon storage to 90 cm depth were assessed using linear mixed-effects [14-16]. The DAYCENT earth system model was calibrated using measured data and used to make predictions of soil organic carbon storage capacity to 30 cm depth, and greenhouse gas emissions for 2016-2050, the equations for which were derived from [17]. The carbon added with the compost applications (270, 675 and 1350 g m^2 respectively) is included in the final SOC sequestration amount as the DAYCENT model accounts for C additions and subsequent losses within its simulated soil processes. This should not be considered a life-cycle analysis, as emissions generated during fertilizer production and composting were not considered in the final GHG calculations (**Table 2**).

Results: *Crop grain yield (**Fig 3**)*- For wheat, the highest compost application was consistently higher yielding than all other treatments in all years. In 2019, and only in 2019, the 25,000 kg compost treatment also had greater yields than both the no fertilizer, and fertilized control applications. Pea yield was unaffected by compost.

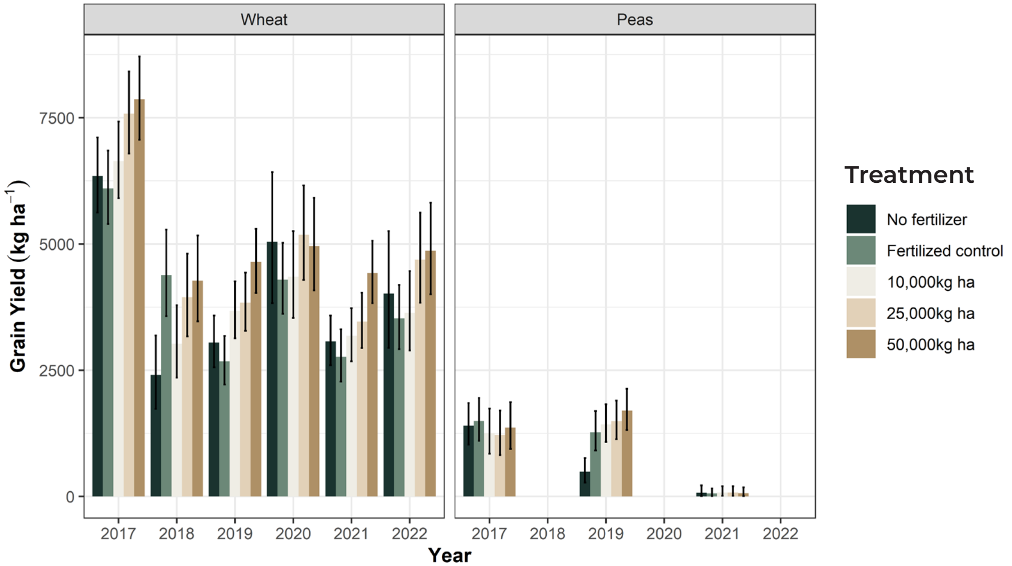


Figure 3: Estimated means (± 95% CI) for the interactive effects of compost treatment, year, and crop type on grain yield (kg ha^{-1}) non-overlapping error bars indicate statistically significant differences between conditions.

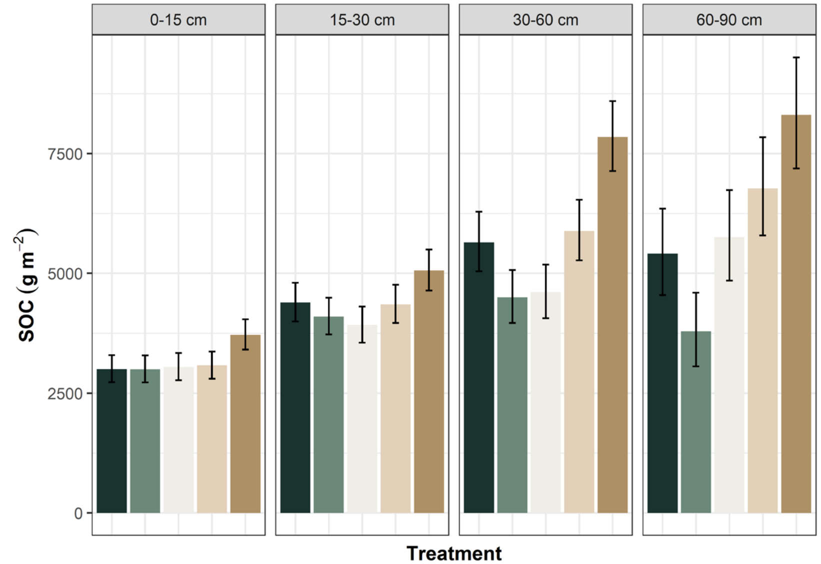


Figure 4: Estimated means (± 95% CI) for the interactive effects of compost treatment and sampling depth on SOC (g m^2). Non-overlapping error bars indicate significant differences between conditions at α= 0.05.

*Soil organic carbon storage at depth (**Fig 4**)* – Near the soil surface (0-15 cm and 15-30 cm), only the highest application of compost increased soil carbon compared with no compost or the fertilized control (business-as-usual). At 30-60 cm depth, there was no SOC difference between the no compost and 25,000 kg compost treatments, both of which were ~13% greater than the 5,000 and 10,000 kg applications. **At 30-60 cm the highest application of compost demonstrated the greatest increase in SOC and at 60-90 cm both the 25 and 50,000 kg applications increased SOC storage.**

*DAYCENT model predictions of SOC storage 2016 – 2050 (**Fig 5**)* – The WF systems were predicted to lose up to 12% and gain up to 0.01% SOC, depending on the amount of amendment added. The WWPF systems lost ~-0.03% and gained up to 17% SOC between 2016 and 2050. Note that SOC storage using DAYCENT can only be predicted for the 0-30 cm depth, so it does not capture the increase in SOC storage seen at greater depths in the experimental study.

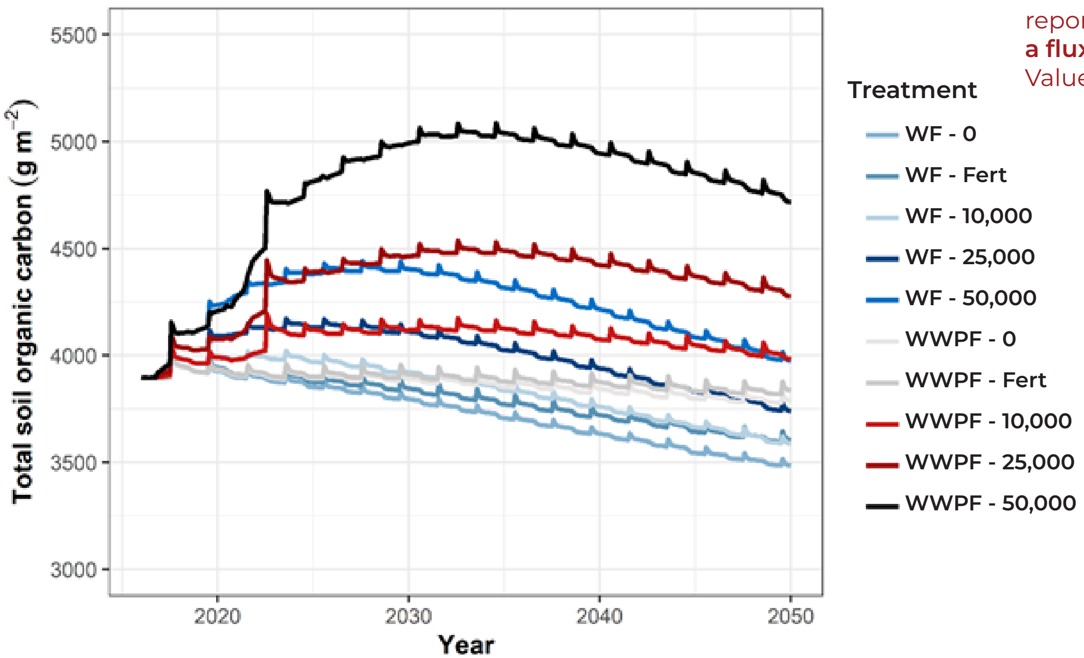


Figure 5: DAYCENT model predictions for 2016-2050 of SOC storage between rotations and compost treatments (applied in kg ha^{-1}). WF = Wheat-fallow, WWPF = Wheat-pea-fallow. Note that the initial compost amount has not been removed from these predictions.

Table 2: Greenhouse gas (GHG) calculations as modeled by DAYCENT, reported as grams CO_2 equivalents (g CO_2e). **A positive value indicates a flux to the atmosphere while a negative value indicates a GHG sink.** Values shown are the annual averages for the period 2016-2050.

Treatment	N_2O CO_2e (g m^2)	CH_4 CO_2e (g m^2)	Soil CO_2e (g m^2)	**Total CO_2e**
WF 0	746.6	-118.6	1583.3	**2211.3**
WF Fert	1006.5	-132.6	1430.8	**2304.7**
WF 10000	839.8	-125.2	1211.8	**1926.4**
WF 25000	983.5	-119.7	666.5	**1530.3**
WF 50000	1212.4	-112.9	-176.1	**923.4**
WWPF 0	970.2	-108.6	461.1	**1322.7**
WWPF Fert	1126.7	-123.8	376.1	**1378.9**
WWPF 10000	1112.1	-117.0	-338.9	**656.3**
WWPF 25000	1358.4	-109.8	-1342.8	**-94.2**
WWPF 50000	1782.6	-106.2	-2998.9	**-1322.6**

*Net greenhouse gas emissions (**Table 2**)*– Since neither nitrous oxide nor methane emissions from soils were measured, net greenhouse gas emissions could only be estimated with models. Wheat production systems have been reported to be both net-zero and net emitting systems [6], **net-emissions being common and expected for intensively managed, food producing systems under conventional management**. In this case study, all systems except the WWPF 25 and 50, 000 kg compost applications were predicted to be net-emitting between 2016 - 2050. Total emissions were lowest under the highest application of compost for both rotations and were also overall lower in the WWPF system. N2O emissions were predicted to be lower than fertilizer application under 10 – 25,000 kg compost in the WF system, but compost tended to increase N2O emissions compared with fertilizer in the WWPF system. Overall, the highest rate of sequestration was ~0.38 T ha-1 per year, and the highest net emissions were ~0.67 T ha-1 per year. **Under both rotations, fertilizer application produced emissions that exceeded those under compost application.**

Discussion

- A single high application of compost in one year, can continue to **stimulate crop growth for years** after initial application. This effect has the potential to improve carbon allocation belowground, contributing to soil organic carbon formation.
- A single high application of compost **increases soil organic carbon in deeper soil layers.** This is particularly important when assessing the permanence of organic amendments, given deep soil carbon has a higher residence time in soil (years to millennia) compared with carbon stored near the surface.
- For drylands, this storage of soil organic carbon at depth may also be i**mportant for soil water retention**, given that SOC helps maintain soil water. This is an important consideration as climate change continues to increase the duration and intensity of drought periods, threatening crop production.
- Modeling results suggest that **applying compost may not only increase crop yield but reduce net on-farm GHG emissions** compared with fertilizer.
- To maximize GHG benefits, **compost must be applied in high amounts,** and potentially more frequently than the single application done in this study. If water limitations allow, combining compost with **more consistent ground cover** (via cover crops or more frequent cash crops in rotation) may achieve higher accumulation of SOC.
- **Earth system models** like DAYCENT - only able to simulate soil processes to 30 cm depth - **cannot show the potential for more permanent storage of SOC at depth,** and therefore **may not fully capture the full agricultural and climate benefits possible from application of organic amendments**.

Photo: Aaron Esser

Key Messages for Legislature

Despite the large number of acres and the economic importance of drylands in Washington, data on organic amendments applied in drylands is scarce. **More dryland research is necessary.**

Many methods of measuring and verifying soil organic carbon do not consider that stored at depth. **Carbon accumulation at depth is a long-term storage effect that is not currently being considered in carbon accounting and *cannot be ascertained from modeling studies alone.***

There is increasing evidence that soils that are furthest from their capacity to store SOC, including but not limited to dryland soils, have the highest rates of SOC accrual with management change [1]. T**his is an important but presently underrepresented consideration for maximizing carbon farming efforts**. Many dryland systems are far from their capacity, and account for the largest acreage of any system across Washington.

Organic amendment case study 2: Puyallup vegetable production

Tillage operations at the Puyallup research farm

Compost production at the WSU facility

Vegetable harvest from the Puyallup compost trial

Photos: Doug Collins

Site description: A long-term compost study site was established at the Washington State University Research and Extension Center Organic Farm in Puyallup, in 2003. Details of the full experiment setup are available [18, 19]. The drip-irrigated field site is situated on fine sandy loam soil with an average of 1041 mm of precipitation annually. Primary (cash) crops included winter squash and broccoli (transplanted), and winter wheat and spinach (direct seeded). These crops were grown in rotation with either a fall planted cover crop – a 50:50 mixture of cereal rye (*Secale cereale* L.) and hairy vetch (*Vicia villosa*) seeded at 134 kg ha-1 (119.5 lb. ac.), or a relay (interseeded) cover crop of hairy vetch at 56 kg ha-1 (49.96 lb. ac.) Vegetable crops were planted in April-May of each year and harvested in August-September and fall cover crops were seeded in September of each year, terminated, and residue incorporated before re-planting the vegetables.

Experimental treatments: Between September 2003-2014, broiler litter and on-farm mixed compost, both produced on-farm at WSU were surface applied annually to provide similar amounts of available nitrogen between each treatment (6000 kg ha-1 of broiler litter and 38,000 kg ha-1 of mixed compost). This resulted in average carbon inputs of 1760 kg ha-1 yr-1 (1570.2 lb. ac) of C from the broiler litter (low C input), and 6250 kg ha-1 yr-1 (5576 lb. ac) of C from the mixed compost (high C input). Each treatment had four replicates. While two different tillage treatments were used in the study, this project modeled carbon in the plots tilled with a rotary spader. Spader-tillage (rotary spader, 1-2 passes at 1.3 km h-1 to 25 cm) was used prior to fall cover crop seeding in the fall-planted treatment and to incorporate cover crop residue in the spring in both fall-planted and interseeded treatments.

Sampling: Vegetable and cover crops were harvested and quantified annually. Soil samples were analyzed for soil organic carbon in 2008, 2012 and 2022. Full experimental results from the years 2006-2013 are available in other publications [18].

Statistical analysis and GHG modelling: Cover crop yields and soil organic carbon storage by compost application type were assessed using linear mixed-effects modelling. Compost influences on cash crop yield are reported from existing published results [18]. The DAYCENT model was calibrated using measured data and used to make predictions of soil organic carbon storage capacity and greenhouse gas emissions for 2003-2050. Because almost none of the cash crops in the study system are parameterized in the DAYCENT model, tomatoes were used as the default (cash) crop. Only the fall-planted cover crop treatments were simulated given the difficulty in accurately modeling two different crops being grown at the same time. Emissions generated during composting were not considered in the final GHG calculations (**Table 3**), the equations for which were derived from [17].

Results: *Crop yield (**Fig 6**)* –Per the final harvest conducted in 2012, no yield differences were observed between the broiler litter and on-farm mixed compost treatments in any year [18]. However, cover crop yield increased by ~17% under the on-farm compost addition.

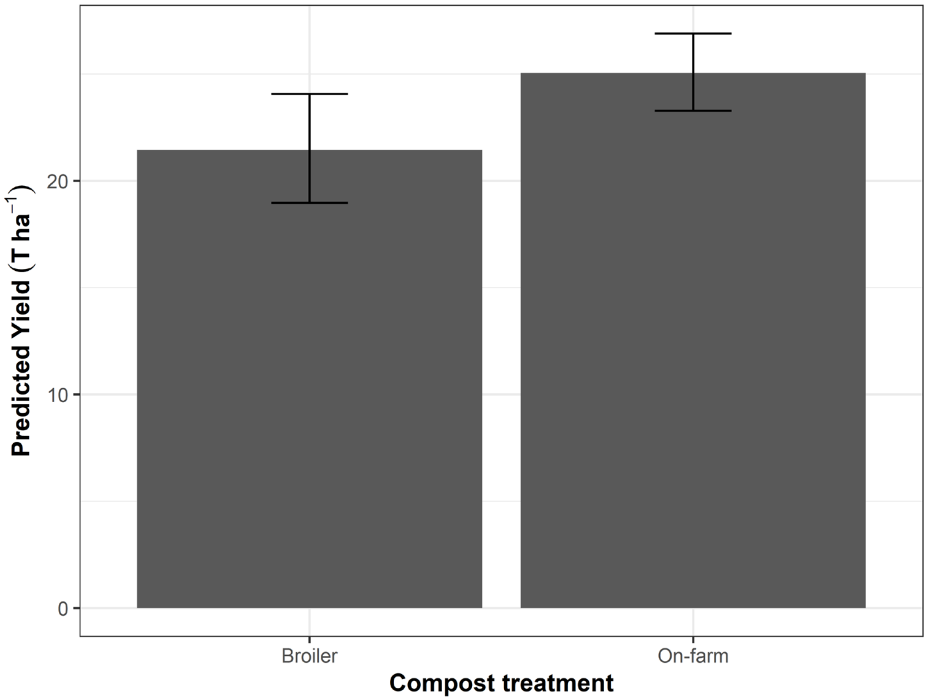


Figure 6: Estimated means (± 95% CI) for the effect of compost type on cover crop yield (T ha^{-1}). Non-overlapping error bars indicate significant differences between conditions at α= 0.05.

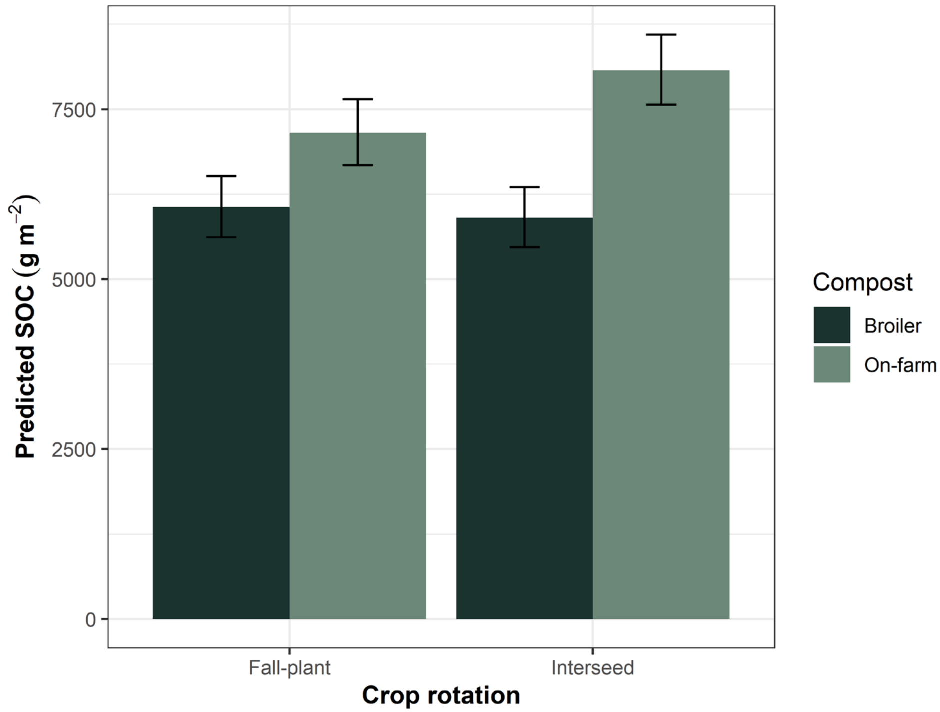


Figure 7: Estimated means (± 95% CI) for the interactive effects of crop rotation and compost treatment on SOC (g m^2). Non-overlapping error bars indicate significant differences between conditions at α= 0.05.

*Soil organic carbon storage (**Fig 7**)*– The on-farm compost increased SOC to a greater extent than the broiler litter, and this effect was greater in the interseeded crop rotation. SOC content did not differ significantly between measured years (2008, 2012, and 2022).

*DAYCENT model predictions of SOC storage 2003 – 2050 (**Fig 8**)* –The broiler litter compost was predicted to lose ~28% soil carbon, and the mixed compost ~25% from 2003-2050. **Because there was no fertilizer or non-amendment control in this study, it is impossible to estimate whether there would be SOC benefits compared to a no-compost control.** However, given that soil C inputs from the mixed compost treatment (6250 kg ha^{-1} yr^{-1}) were approximately 250% greater than the broiler litter (1760 kg ha^{-1} yr^{-1}), it is possible to see that despite a far greater C input under the mixed compost treatment, the C inputs were not predicted to persist over the full modeled time-frame (with all other farming practices continuing).

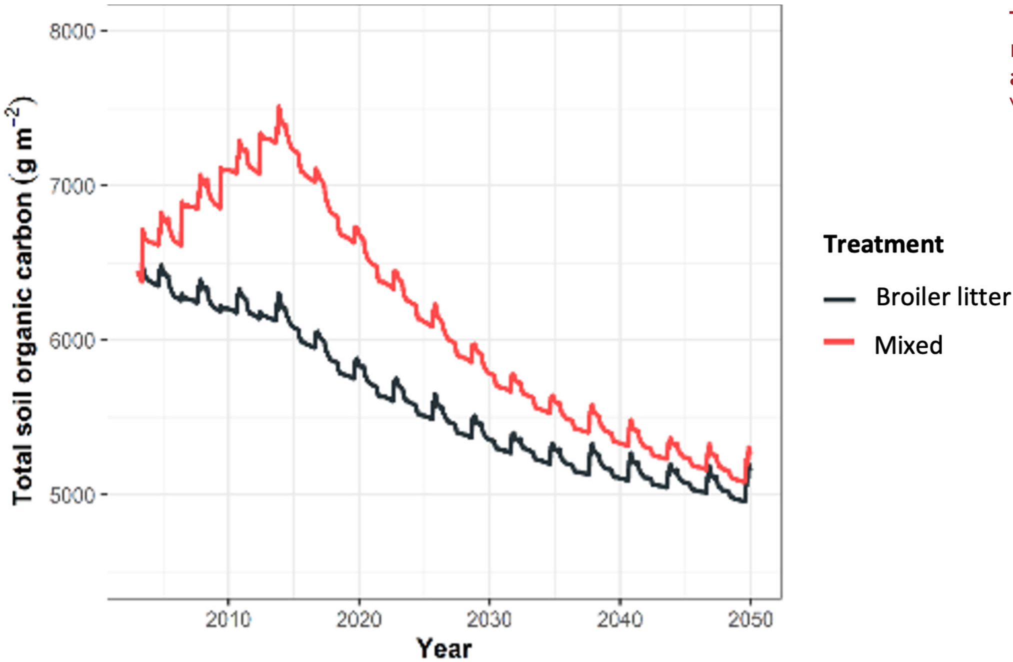


Figure 8: DAYCENT model predictions of SOC storage (2003-2050) between rotations and compost treatments. **Note** that the initial compost amount is included in these predictions.

Table 3: Greenhouse gas (GHG) calculations as modeled by DAYCENT, reported as grams CO_2 equivalents (g CO_2e). **A positive value indicates a flux to the atmosphere while a negative value indicates a GHG sink.** Values shown are the annual averages for the period 2003-2050.

Treatment	N_2O CO_2e (g m²)	CH_4 CO_2e (g m²)	Soil CO_2e (g m²)	Total CO_2e
Broiler Litter	4145.2	295.0	5183.5	**9623.8**
Mixed compost	5658.1	359.9	4786.9	**10805.0**

Photo: Doug Collins

<u>*Net greenhouse gas emissions (**Table 3**)*</u>– All treatments were predicted to be to net-emissions. It is not a surprise that these agricultural systems would be net emitting, as there are minimal non-harvested residue inputs, and emissions calculated here are similar to those reported in other temperate climate, small-scale vegetable farming systems in Washington [20]. The lowest predicted emissions were under the broiler litter with ~2.04 T ha^{-1} per year, and the highest under the mixed compost with ~2.29 T ha^{-1} per year. The higher emissions under the mixed compost were primarily driven by the N_2O emissions. Soil C sequestration from each compost treatment did not differ significantly. Remember that without a "business-as-usual" baseline, it is not possible to compare the climate impact of amendments in this system to conventional practices.

Discussion

- **Soil organic carbon** storage in temperate vegetable systems can be **increased by combining organic amendment application and cover cropping**.
- Although the two tested composts had similar available nitrogen, **the compost with a higher carbon to nitrogen ratio yielded more cover crop biomass.**
- In non-water-limited vegetable farming systems, nitrogen-fixing cover crops may increase soil carbon under high C input organic amendments, as the **compost addition may stimulate microbial activity in soil and enhance positive plant-soil feedbacks** favoring soil C sequestration.
- Enhanced plant-soil feedbacks and development of SOC can improve nutrient cycling in vegetable cropping systems, however more mechanistic understanding is required.
- Organic amendments **will not necessarily store SOC long-term in temperate systems under intensive tillage, even when supplied in large quantities** (> 6000 kg ha^{-1} annually for 10 years).
- Vegetable production systems are generally net-emissions owing to high fertilizer inputs and limited application of cover cropping to enhance soil C sequestration [21].
- However, without the ability to compare these organic amendment treatments with a 'business-as-usual' baseline (i.e.: a synthetic fertilizer control) it is not possible to quantify to what extent the studied organic amendments may influence CO_2e emissions compared to the use of inorganic fertilizers.

Photo: Doug Collins

Key Messages for Legislature

It is well understood that soils have a physical limit to which they can accumulate carbon which is largely bounded by clay content. Given high inputs of fertilizer, water, and sufficient plant growth, **it is more likely that irrigated agricultural soils in temperate regions, such as the ones in this experimental system, may be nearer to their mineralogical capacity to store carbon.**

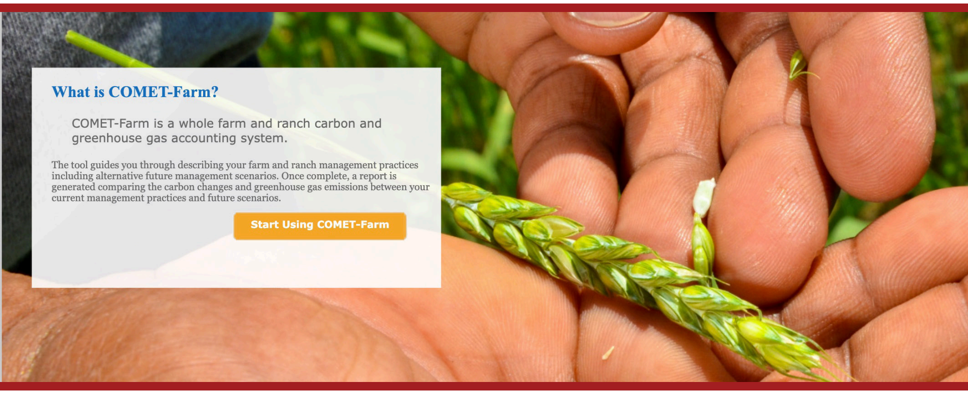
Because this study did not include a fertilizer-only treatment, it is impossible to compare emissions to "business as usual", as was possible in the dryland case study.

This study suggests that a **soil amendment with a high C:N ratio** (that also provides sufficient N for plant growth) **can positively influence cover crop growth which can significantly increase soil carbon inputs over time.** This is particularly notable given that the soils are potentially unlikely to be substantially below their carbon storage capacity. However, a **significant limitation to soil carbon accumulation and long-term storage in agricultural systems is tillage, which was intensive in the study system**.

SECTION 3.

COMPARING THE FUNCTION AND PERFORMANCE OF AVAILABLE MODEL TOOLS

DAYCENT, COMET Farm, Cool Farm, WaCSE (Washington Climate Smart Estimator)



Photos: Available at (left) comet-farm.com (top) rel.colostate.edu/projects/century/index.php (bottom left) wsda.shinyapps.io/WaCSE/ (bottom right) coolfarmtool.org

Methods: Farm management and measured data from Section 2 case studies were used to initialize and produce GHG emissions and SOC storage predictions from four available model tools. **The models in this study were chosen not because this is an exhaustive list, but because they represent the types and range of model tools available for GHG emissions calculation globally. These include models that use Tiers 1, 2 and 3 emissions factors and management data.** Model performance between the DAYCENT and COMET-Farm simulations was quantified because, of the models employed, these were the only two for which field data could be used to verify model predictions.

What are model tiers? A tier represents a level of methodological complexity employed within a model. The three tiers are categorized depending on where emissions factors and activity/site management data are derived and as the tiers increase, models become more demanding in terms of complexity and data requirements. Tier 1 models use the most basic data and usually employ Intergovernmental Panel for Climate Change (IPCC) recommended country-level default values that are not site-specific. Tier 2 models require an intermediate level of complexity and include some site-level data. Tier 3 models are the most complex, require the greatest amount of data and can provide site-specific estimates.

Often, models employ a mixture of tiers to estimate emissions, an approach that often reflects information availability or the need to simplify use. In some cases, calculation of emissions from agricultural operations will combine different levels of site-specific management data with Tier 1 emission factors to estimate emissions from varied sources on-farm.

Model descriptions: 1) DAYCENT (Tier 3): An extensively published earth system model originally developed in 1998 and primarily used for academic purposes, **2) COMET-Farm (Tiers 1,2,3)**: An online tool developed by the USDA and Colorado State University and released in 2005, modified from the DAYCENT model, **3) Cool Farm (Tier 1,2):** An online greenhouse gas, water, and biodiversity calculator for farmers developed in the United Kingdom in 2010, **4) WaCSE (Tier 1):** the Washington Climate Smart Estimator: Developed in 2022, WaCSE is an application-based, online tool adapted from the COMET-Planner tool (http://comet-planner.com/) to establish WA-county-specific estimates of changes in GHG emissions resulting from changes to land management practices in line with USDA-NRCS conservation practices. Model-specific features and input potentials are detailed in **Table 4**.

Model data input (Case study 1; Dryland wheat, 2016-2025) DAYCENT: Chosen historic management scenario (Pre-1980): non-irrigated winter-wheat under intensive tillage. Baseline cropping (2000-2015): non-irrigated winter wheat under no tillage. Cropping scenarios were initialized using low-harvest winter wheat and Austrian winter peas, with compost additions (C:N ratio, total nitrogen inputs and total amount applied) parameterized from field values. Model calibration was achieved by examining and matching plant inputs to measured crop yields and initial measured SOC content. **COMET-Farm:** Chosen historic management scenario (Pre-1980): non-irrigated grain-fallow under intensive tillage. Baseline cropping (2000-2015): non-irrigated winter wheat under no tillage. Cropping scenarios were initialized using measured yield values for winter wheat and dry field pea, with compost additions (C:N ratio, total nitrogen inputs and total amount applied) parameterized from field values. The model did not allow parameterization using measured SOC values. **Cool Farm:** One year (2016) winter wheat rotation with the differing compost applications was simulated. Because it was not possible to simulate a fallow year following the winter wheat/pea, only one year of prediction was done using Cool Farm. **WaCSE**: A practice change was implemented on non-irrigated croplands in Lincoln County, Washington using CPS 590, and interpreted the GHG emissions reductions for "replace synthetic nitrogen fertilizer with compost (C:N ratio 15, based on the compost analysis for the trial).

Model data input (Case study 2; Puyallup vegetable trial, 2005-2015) DAYCENT: Chosen historic management scenario (Pre-1980): non-irrigated fallow-grain under intensive tillage. Baseline cropping (1980-2002): irrigated corn under intensive tillage. Cropping scenarios initialized using tomatoes, with compost additions (C:N ratio, total nitrogen inputs and total amount applied) parameterized from field values. Model calibration was achieved by examining and matching plant inputs to measured crop yields and initial measured SOC content. **COMET-Farm:** Chosen historic management scenario (Pre-1980) irrigated annual crops in rotation with intensive tillage. Baseline cropping (2000-2002) irrigated corn under intensive tillage and between 2003-2005 the cropping scenario was initiated. Cropping scenarios initialized using predicted yield values for the cash crop with compost additions (C:N ratio, total nitrogen inputs and total amount applied) parameterized from field values. The model did not allow parameterization using measured SOC values. **Cool Farm**: One year (2005) tomato rotation with the differing compost applications, and one year grass-clover rotation were simulated and summed to achieve full estimation of emissions. **WaCSE**: A practice change was implemented on irrigated croplands in Pierce County, Washington using CPS 590, and interpreted the GHG emissions reductions for "replace synthetic nitrogen fertilizer with chicken broiler manure" for the broiler litter, and "replace synthetic nitrogen fertilizer with compost (C:N ratio 15)" for the mixed compost addition.

Photo: LoweStock- adobestock.com

Statistical analysis (Model performance): It was only possible to statistically compare SOC storage predictions between measured and modeled values for the DAYCENT and COMET Farm models. For this purpose, model spin up values (the initial SOC content of the soil as determined by the historical management and baseline scenarios), and ongoing prediction values for SOC (the values predicted by the model during the field trial years) were compared against measured SOC values between different cropping conditions and years (Case study 1) and compost treatments (Case study 1 & 2) using analysis of variance in R [22].

Model performance (Case study 1; Dryland wheat, 2016-2025): Differences between modelled vs measured values were significantly different between the two models regarding the 50,000 kg treatment ($p<0.005$; **Fig 9**). In the 50,000 kg compost treatment the DAYCENT model on average underestimated the actual SOC content by 1%, compared to the COMET-Farm model which overestimated the value by ~24%. There were no differences between the models regarding variances from measured values for any other compost treatment. As well, measured vs modelled values across the two models differed by crop rotation ($p<0001$). For the wheat-fallow rotation, DAYCENT tended to underestimate SOC content by ~14%, while COMET overestimated it by ~10%. For the winter wheat-pea-fallow rotation, DAYCENT underestimated actual SOC content by ~5%, and COMET overestimated it by ~20%. There were no differences between the models regarding variance from actual SOC values for different years.

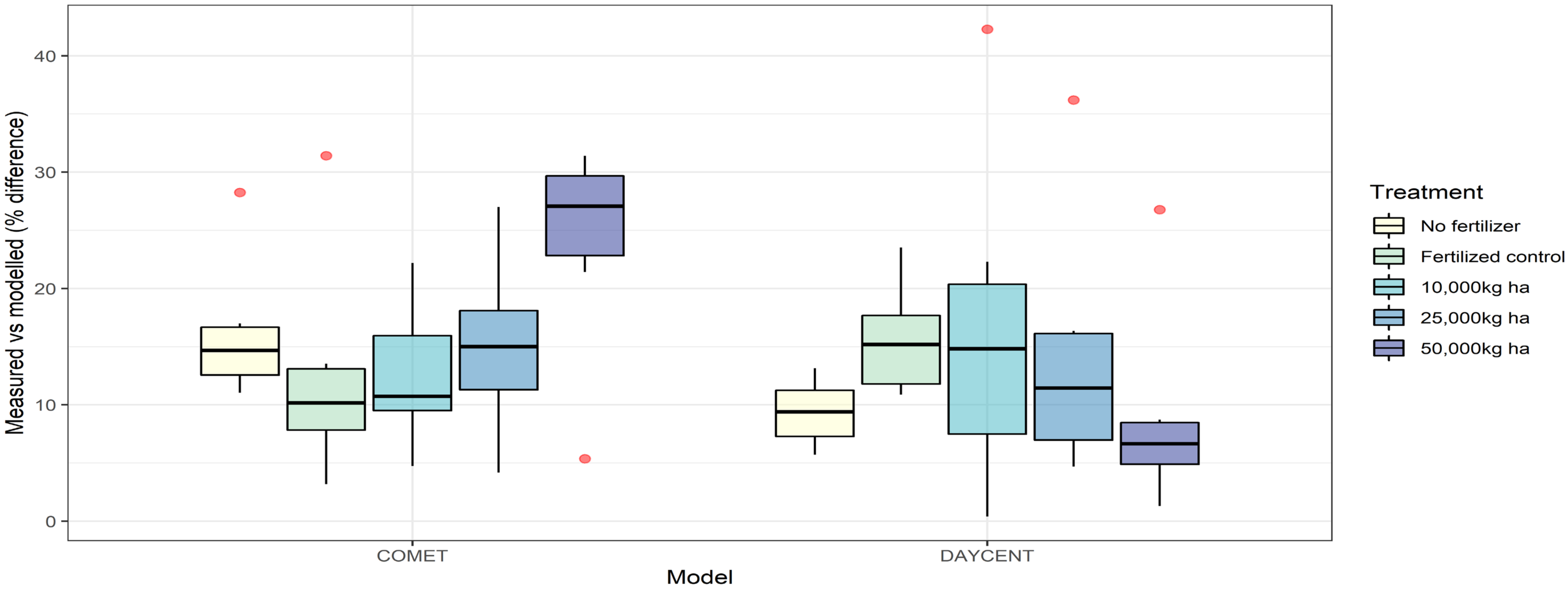


Figure 9: *Case study 1 (dryland wheat trials).* Percentage deviation between measured and modelled values (bias) for SOC content by compost treatment for the DAYCENT and COMET-Farm models. Mean values are indicated by the solid black line within each box whereas the rest of the box and whisker indicates the 1st,2nd, 3rd, and 4th interquartile ranges of the values. Shaded red dots indicate outlier values.

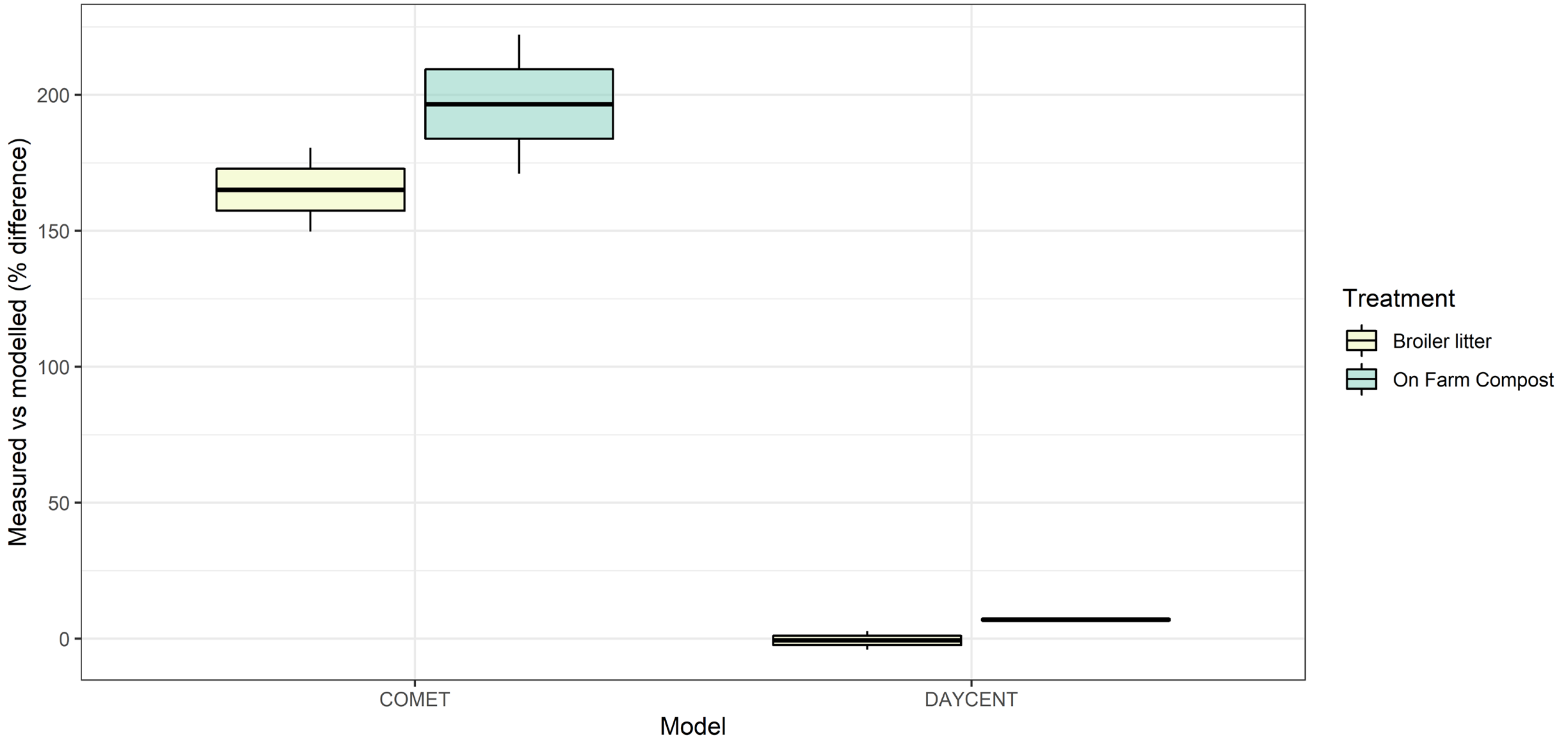


Figure 10: *Case study 2 (Puyallup vegetable trials).* Percentage deviation between measured and modelled values (bias) for SOC content between DAYCENT and COMET-Farm models.

Model performance (Case study 2; Puyallup vegetable trial, 2005-2015): Differences between modelled and measured values were significantly different between the two models ($p<0.005$; **Fig 10**). Regardless of compost treatment, the DAYCENT model on average overestimated the actual SOC content by 3%, compared to the COMET-Farm model which overestimated the value by ~80%. These disparities were likely due to the initial overestimation of SOC content by the COMET-Farm model.

Photo: Kirsten Ball

Table 4: Input requirements and useability between the DAYCENT, COMET-Farm, Cool Farm and WaCSE models/tools.

	Site & Climate		Soil		Land Management			Cropping			Inputs				Other GHG Sources		Useability		
	Climate & Weather	Geographical Location	Texture / Water Holding Capacity / Bulk Density	Initial SOC / SOM Content	Historical Management	Conservation Practice Status	Tillage / Ground Operations	Crop Type	Crop Rotation	Planting & Harvest Dates	Fertilizer	Organic Amendments	Irrigation	Grazing	Fuel & Energy	Transport	Predictive Scope (years)	Data Requirement	Required Operational Skill Level
DAY-CENT	Fully user-defined	Fully user-defined	Fully user-defined	Fully user-defined	Fully user-defined	Fully user-defined	Fully user-defined	External data/tools	Fully user-defined	Fully user-defined	Fully user-defined	Fully user-defined	Fully user-defined	Fully user-defined	Not defined	Not defined	100+ years	High	High
COMET Farm	External data/tools	External data/tools	External data/tools	External data/tools	Drop down	Drop down	Drop down	Drop down	Drop down	Fully user-defined	Fully user-defined	Drop down	Fully user-defined	Drop down	External data/tools	External data/tools	10 years	Low	Med.
COOL Farm	Not defined	Not defined	Drop down	Fully user-defined	Not defined	Drop down	Drop down	Drop down	Not defined	Not defined	Fully user-defined	Drop down	Fully user-defined	External data/tools	External data/tools	External data/tools	1 year	Low	Low
WaCSE	External data/tools	Drop down	External data/tools	External data/tools	Not defined	Drop down	Drop down	Not defined	Not defined	Not defined	Drop down	Drop down	Drop down	Drop down	Drop down	Not defined	1 year	Low	Low

Fully user-defined via manual entry or input flexibility

Defined from external data/other related tools

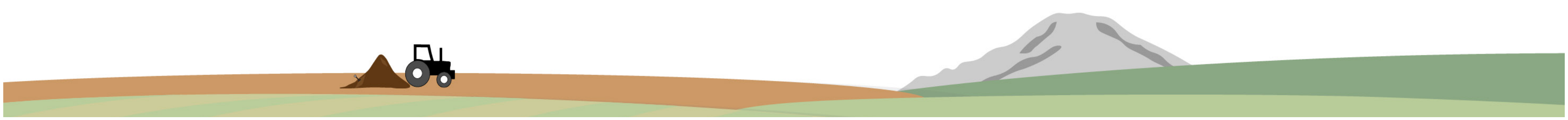
Defined through drop down (restricted choices)

Not defined

The DAYCENT model is the daily time step version of the CENTURY model and is routinely used to simulate carbon and nitrogen dynamics in forests, grasslands, and croplands. It has been widely applied to simulate agricultural management practices including the application of organic amendments to croplands in the US. DAYCENT provides estimates of SOC sequestration and GHG emissions in response to land management change and can be initialized and calibrated using field data such that the model estimates exhibits a low-level of bias. However, the model requires a high-level of expertise to achieve this level of accuracy. As well, using field data to verify model predictions requires a high level of skill and understanding of the model outputs. Several important crops to Washington are not currently represented in the model, but (with supporting data) can be parameterized and/or existing crop parameters altered to model these crops. The ability to grow an infinite number of crops in rotation provides a significant benefit over the other tools for complex rotations. As well, the model allows the crops to be responsive to fertilization, amendments, precipitation, and temperature which fluctuate the crop growth during the season, allocating varying amounts of carbon to the soil pool. Simply, it is more sensitive to field scale changes than the other models.

The COMET-Farm tool is a user-friendly option for estimating SOC in response to management changes and has been widely adopted to estimate GHG emissions on US farms for the purpose of carbon accounting. In the case where the background initialization data approximates field measured values, it demonstrated relatively low bias for this metric. However, there were problems where initial SOC content was incorrect (Case study 2). This problem could be circumvented if the model allowed the user to alter these data using a custom value. There are several important crops to Washington, like apples, which are not included in the tool. For case study 2 (Puyallup), where broccoli and squash had to be modeled as tomatoes, there is also greater potential bias from modeling the "most similar available" crop arising from the fact that the crop parameters cannot be manipulated in the model interface. The ability to grow up to three different crops in a single year is a benefit over comparable models like COOL Farm. Further, COMET-Farm allows the user to carry over perennial crops from one year to the next without replanting and thereby considers legacy effects of nutrient use and input by the previous crop. It was possible, but not simple to use the COMET-Farm tool output to verify changes to soil organic carbon, making it difficult to ascertain validity of predictions made for the 10-year timeframe. It is possible that using COMET-Farm for verification purposes may be beyond the ability of most average users.

Cool Farm is a user-friendly option for estimating SOC in response to management changes and has been widely adopted globally to estimate on-farm GHG emissions. It was not possible to verify the GHG emissions estimates from the output data provided by the platform because these data are not made available, therefore model bias cannot be commented on. Unlike COMET-Farm, Cool Farm allows the user to specify custom values for initial SOC content which may reduce the potential for bias arising from this metric. However, several important crops to Washington were not available as choices in the platform, and it is not possible to model crops in rotation or to carry over perennial crops from year to the next. Cool Farm also only allows the user to model one year of emissions at a time. Given the fluctuating nature of GHG emissions related to interannual climate variability, it is likely that having the capacity to model more than one year of emissions data to obtain average yearly values may produce more accurate estimations. Finally, it was noted that Cool Farm did not alter the amount of soil organic carbon entering the system in response to organic amendment addition. For this reason, this model is likely unsuitable to accurately estimate changes to SOC content under organic amendments.



WaCSE is a user-friendly adaptation of the COMET-Planner tool (http://comet-planner.com/) developed by the WSDA to support quantification of Washington county-specific GHG benefits for the Washington Sustainable Farms and Fields program. It was not possible to verify the GHG emissions estimates from the output data provided by the platform, therefore model bias cannot be commented on. As the tool uses Tier 1 methods, it requires very little site-specific data and therefore cannot account for different cropping systems or rotations, and from the perspective of organic amendments, because management activity is specified using pre-defined practice change scenarios it is not possible to alter the amount of compost added to the system. Therefore, SOC benefits resulting from organic amendment application are not site-specific using this tool.

Table 5 (a): Average yearly emissions by model for the period of Case study 1 (CS1): 2016-2025. Only one year of emissions data was able to be calculated for the COOL-Farm and WaCSE tools. Because the WaCSE tool does not use a baseline scenario for Case study 1, care should be taken in directly comparing these numbers with the other estimates. *BAU = 'business as usual', synthetic fertilizer application. No CO_2e emissions costs from compost production were included in this analysis. A positive value indicates a flux to the atmosphere while a negative value indicates a GHG sink.

	Case Study 1 (Dryland Wheat)									
	CO_2 (g m² yr⁻¹)		N_2O (g m² yr⁻¹)		CH_4 (g m² yr⁻¹)		Total CO_2 eq (g m² yr⁻¹)		Total CO_2 eq (T ha⁻¹ yr⁻¹)	
Scenario	**BAU***	**50,000 kg ha-1**	**BAU**	**50,000 kg ha-1**	**BAU**	**50,000 kg ha-1**	**BAU**	**50,000 kg ha-1**	**BAU**	**50,000 kg ha-1**
DAYCENT	-9.38	-393.95	45.33	99.35	-3.73	-3.32	32.22	-297.92	0.32	-2.98
COMET-Farm	-19.19	-115.27	127.10	452.30	0.00	0.00	107.91	337.03	1.08	3.37
COOL Farm	-37.51	-37.51	42.77	170.34	0.00	0.00	5.26	132.83	0.05	1.33
WaCSE (practice change)	*NA*	*49.42*	*NA*	*-12.35*	*NA*	*0.00*	*NA*	*37.07*	*NA*	*0.37*

For case study 1 (dryland wheat), all models/tools, except for WaCSE predicted net SOC sequestration between 'business as usual' (synthetic fertilizer application) and application of 50,000 kg ha^{-1} of compost. Estimates ranged from 0.37 T ha^{-1} for COOL Farm, 0.96 T ha^{-1} for COMET-Farm and 3.84 T ha^{-1} using DAYCENT. *It is important to note that COOL Farm does not add carbon to the soil pool from amendments, nor increase crop growth in response to organic amendments, therefore the SOC sequestration benefit was static between conditions.* Under the practice change scenario CPS 590 (Nutrient Management), WaCSE predicted a 0.49 T ha^{-1} yr^{-1} loss of SOC. Increased N_2O emissions between BAU and high compost addition ranged between 0.54 T ha^{-1} yr^{-1} for DAYCENT, 1.27 T ha^{-1} yr^{-1} for COOL Farm and 3.25 T ha^{-1} yr^{-1} for COMET-Farm. WaCSE estimated a 0.12 T ha^{-1} yr^{-1} reduction in N_2O emissions under the practice change.

Table 5 (b): Average yearly emissions by model for the period of Case study 2 (CS 2): 2006-2015.

	Case Study 2 (Puyallup Vegetable Trial)									
	CO_2 (g m² yr⁻¹)		N_2O (g m² yr⁻¹)		CH_4 (g m² yr⁻¹)		Total CO_2 eq (g m² yr⁻¹)		Total CO_2 eq (T ha⁻¹ yr⁻¹)	
Scenario	**Broiler**	**Mixed**	**Broiler**	**Mixed**	**Broiler**	**Mixed**	**Broiler**	**Mixed**	**Broiler**	**Mixed**
DAYCENT	109.28	-156.47	111.92	154.53	7.37	8.98	228.57	7.04	2.29	0.07
COMET-Farm	-571.15	-1585.22	400.85	722.68	0.00	0.00	-170.30	-862.54	-1.70	-8.63
COOL Farm	-258.72	-258.72	267.92	269.97	0.00	0.00	9.20	11.25	0.09	0.11
WaCSE (practice change)	*19.76*	*34.59*	*-12.35*	*-9.88*	*0.00*	*0.00*	*7.41*	*24.71*	*0.07*	*0.25*

For case study 2 (Puyallup vegetables), all models/tools, except for WaCSE, predicted net SOC sequestration between broiler litter and mixed compost additions. Predictions were in the range of 2.58 T ha^{-1} yr^{-1} for COOL Farm, 2.65 T ha^{-1} yr^{-1} for DAYCENT, 10.14 T ha^{-1} yr^{-1} for COMET-Farm and net C emissions of 0.15 T ha^{-1} yr^{-1} for the WaCSE simulated practice change. Increased N_2O emissions between broiler litter and mixed compost addition ranged between 0.02 T ha^{-1} yr^{-1} for COOL Farm, 0.42 T ha^{-1} yr^{-1} for DAYCENT, and 3.21 T ha^{-1} yr^{-1} for COMET-Farm. WaCSE estimated a 0.12 T ha^{-1} yr^{-1} reduction in N_2O emissions under the broiler litter practice change, and 0.09 T ha^{-1} reduction under the mixed compost.

Photo: Doug Collins

Discussion

Our characterization and testing suggests:

DAYCENT (Tier 3): For **detailed, farm specific** estimates using **local climate data and measured soil parameters**. Where the aim is to make **medium to long-term (± 50 years) predictions in complex crop rotations** and where the **user has a high operational skill level** and **the capacity and desire** to integrate **large amounts of measured data** for the purpose of **initializing and calibrating the model**, and where the user wants to **verify model predictions against field measured values**. Our comparison of measured and modeled data suggest that in our two contrasting case studies, parameterization allowed modeled SOC values to come close to measured values.

COMET-Farm (Tier 1,2,3): For **farm specific** estimates using **local climate and soil survey data obtained from databases**. Where the aim is to make **short-term (10 years) predictions in up to three rotational crops per year**, and where the **user has a low-medium operational skill level** and **limited capacity or desire to integrate large amounts of measured data** for the purpose of **initializing and calibrating the tool**, and where the user wants to **verify model predictions against field measured values**. Our comparison of measured and modeled data suggest that in our two contrasting case studies, modeled SOC values were in some cases close to measured values, and in other cases quite far. This suggests that in at least some cases, users should be cautious of using COMET-Farm estimates in the absence of field-measured values.

COOL Farm (Tier 1,2): For **non-farm specific estimates** without integration of **climate data, and some measured soil parameters**, where the aim is to make a single point prediction **(1 year) prediction** for **one crop per year**, and where the **user has a low-medium operational skill level** and **limited capacity or desire to integrate large amounts of measured data** for the purpose of **initializing and calibrating the tool.**

WaCSE (Tier 1): For **Washington State estimates** using **county-rectified MLRA spatial units** for **climate and soil parameters**. Where the aim is to make **a single point prediction (1 year)** of the **non-crop-specific** GHG emissions change from **adopting specific NRCS Conservation Practice Standards** and **where the user has a low operational skill level** and **limited capacity or desire to integrate measured data** for the purpose of **initializing and calibrating the tool.**

Key Messages for Legislature

Considerations for which model tool fits best for the purpose of calculating GHG emissions for carbon farming projects include:

1. **What data is available**, and what resources and funding are available for collecting field-level data?
2. What is the **skill level of the user/s**?
3. Given that model tools have differing data requirements and capabilities which influence model accuracy, **what level of uncertainty is acceptable**? Is this a field-level assessment that demands more data to obtain a higher level of accuracy, or a county-level assessment that is primarily concerned with the overall directionality of the CO2e effect of a practice change?
4. If a high level of uncertainty is not acceptable, **what resources and funding are available to engage personnel** capable of operating more complex models and to collect the needed data for parameterization?

There are a range of well-developed models/tools available to estimate GHG emissions from changing agricultural practices on-farm; each having their pros and cons. *These tools can be broadly defined as those that offer increased site-level accuracy, but which require large amounts of data and operational expertise, versus those that require minimal data and a low-level of user skill but for which there is a trade-off for reduced accuracy and increased uncertainty at the site-scale.*

Part 2:

Assessment of Government Compost Usage

OVERVIEW

Over the last twenty years there has been a large-scale effort to divert organic waste from landfills, building on the foundations of the recycling movement of the 1980's and 1990's. Individuals and political action groups helped enact a diverse array of programs aimed at diverting organic waste from landfills to compost facilities where it could be processed into a soil amendment. Organic waste collection programs are now common throughout the U.S. A challenge to their long-term sustainability in many places has been ensuring adequate demand for the compost produced. While small scale individual purchases of compost are a demand source that can command a high price, it is inadequate for absorbing supply generated from a municipal scale organic waste collection program in most cases.

Among the strategies that have received consideration for absorbing supply, attention has been focused on enhancing agricultural and municipal use. On the agricultural side, farmers have been slow to adopt compost use, and previous studies suggest that barriers include cost, contamination of finished compost with non-compostable waste materials, high barriers to entry such as the cost of compost spreaders, and concern relating to food safety regulations. From an economic standpoint, previous analysis of use in Washington agricultural systems suggests that although there is considerable variability, the value of compost for agricultural use likely exceeds cost in many settings [23].

Since municipalities play a central role in organic waste collection and compost supply, a more direct path to mandating use is to require that municipalities buy back some amount. Municipal procurement requirements are increasingly being incorporated into legislation. In California, SB 1383, which went into effect in 2022, sets municipal compost procurement requirements. The Washington State Legislature passed the Organics Management Law in 2022 (HB 1799) that also sets targets for municipal compost buy-back.

The work on this report was initiated before the passage of HB 1799, but there was time to pivot to consider how best to provide information that would be relevant given the scope and scale of this legislation. What became clear was that systems were not in place in most municipalities to document compost use – either through a buy-back program or other sources – without significant additional effort. The lack of readily available quantitative information made it infeasible to create a reliable database of municipal compost use at this time. Therefore, an important outcome of this report was to warn that documenting use could be challenging for many towns and cities. Developing flexible administrative systems for tracking municipal compost procurement, that work for very small to large cities will be a challenge, but successfully overcoming this problem could reap rewards by generating quantitative information and better insights about what strategies are working across Washington, and how to improve municipal compost use over time.

Faced with the lack of quantitative information, there was a refocusing of the work on (1) providing a qualitative description of levels of current municipal compost use, and (2) understanding perceptions of obstacles to increased municipal compost use. This was done through a survey sent to nearly all municipalities in the state – including all 300 towns, cities, and county governments listed by the Municipal Research and Services Center (www.mrsc.org) – and in-depth conversations with a small number of representative town, city, and county agencies. By providing a range of perspectives on current and potential municipal compost use, this report aims to inform discussions related to meeting the goals of HB 1799.

Photo: William- stock.adobe.com

SURVEY OF COMPOSTERS

Approximately 60 composters were contacted via email, based on a list of commercial and public composters maintained by the Department of Ecology. Responses were returned by 14. The composters who responded varied widely in size with an annual production ranging between 2,000 and 200,000 cubic yards. Most were at the lower end with between 5,000 and 15,000 cubic yards. Among the respondents, self-haul programs were the most common compost feedstock source (8/14) followed by city-sponsored collection programs (6/14), wastewater (5/14), and on-farm collection (3/14). It is important to recognize that this frequency does not correspond to the share by quantity.

Information that survey respondents provided on who is buying compost did suggest that agriculture and municipal demand is lagging, although this can be difficult to document because private contractor purchases of compost may be for municipal projects. A general "other" type of buyer was the most common type of buyer mentioned. Construction firms were the next most common recipient, with six out of 14 composters selling to them. City, county, and state governments were sold to by four of 14. Only two of 14 composters reported selling to farmers. We were not able to collect useful information on compost production costs.

Photo: Cassidy McGhehey

SURVEY ON MUNICIPAL COMPOST PROCUREMENT

Approximately 300 cities, towns, and counties in Washington were contacted with an online survey on compost procurement. We received responses from 60, or a response rate of 20%. Of the 60 that responded, 70% reported that they never use compost. The primary reason given was that they did not have any projects where compost could be used. Another reason given by two respondents, both in Northeast Washington, was that they would like to use compost but did not have a nearby supplier. A third reason given was that compost was not an approved material for potential uses.

The 20 responses that reported some compost uses were sent a follow-up survey to get more detailed information on quantities and budgets. The main finding was that even the local government entities that are using compost either do not know how much they are using or are using very little. Parks and public works directors often know that they use compost, but don't know how much or the amount spent. Treasurers tend not to know because the cost is so low. Among respondents who could estimate a quantity, the most frequent response was that they used approximately 20 cubic yards per year with budgets of less than $1,000. To better understand why procurement was not higher, we followed up with in-depth conversations, which are summarized in the next section.

Based on the responses to these surveys, we were able to characterize four general typologies that can be useful for making sense of the huge diversity that exists across local governments in Washington.

- **Type 1:** Does not use compost because the city is small and does not have parks or capital projects. Examples: Index, Coulee Dam.
- **Type 2:** Does not use compost because compost is not sold nearby. Examples: Pateros, Colville.
- **Type 3:** Uses compost because they have a processing operation (WWTP or self-haul yard waste). Examples: Centralia, Lynden
- **Type 4:** Uses compost because they are a larger city with many projects. Purchase from outside entities. Examples: Kennewick, Kirkland.

IN-DEPTH DISCUSSIONS ON COMPOST SUPPLY AND USE

Following the surveys, there was an effort to have in-depth discussions a mix of small, medium, and large towns and cities across Washington to better understand a representative range of experiences. Small towns and cities included Port Angeles, Port Townsend, and Westport. Large cities were Seattle, Spokane, and Tacoma. Discussions were also conducted with Pierce and Stevens County.

Places where demand exceeds supply: While inadequate demand has been a challenge for many places, Port Townsend and Westport were examples where demand for compost typically exceeds supply locally. Both are small cities, so there isn't nearly as much compost to absorb as in larger municipalities. That said, there may still be useful lessons to learn, especially for the smaller towns and cities across Washington. Port Townsend focuses on yard waste as the primary feedstock and does not allow food waste. This is due to concerns around food waste related to odor and pests, which could increase processing costs. Port Angeles, also located on the Olympic Peninsula and of similar size, has been less successful. One reason cited is that the organic waste drop-off option was little used by the public.

The City of Westport (Grays Harbor County) is another example of a small town with a healthy program. Feedstocks are sewage and tree trimmings, and their primary use is parks. Purchases by the public are also significant. Total amount of compost sold per year is in the range of 170 to 270 yards, which sells out quickly. Westport may serve as a model of how small and rural municipalities can develop robust compost programs that include a mix of private and public sector compost use. Another factor to consider from the Westport experience is that requirements for municipal buyback may crowd out private demand where total demand exceeds supply.

Buyback or specified allotments: The City of Tacoma and Pierce County both have some agreement to receive compost produced from feedstocks collected as part of their organic waste collection. Tacoma has formalized a buyback agreement in the past. Pierce County has an arrangement to receive an allotment of compost at no cost.

Obstacles to expanding municipal compost use: While discussions were wide ranging, there were some common themes that came up as obstacles to expanding municipal compost use. They spanned the entire organic waste stream chain from consumer materials standards (to reduce non-compostable contaminants in compost) to final uses. It is important to emphasize that this is a summary of perceived obstacles. It is possible that some may disagree on whether perceived obstacles are real, but it was beyond the scope of this report to consider that possibility. It is also the case that perceptions alone can be an obstacle, so those differences may highlight areas to target for improved communication.

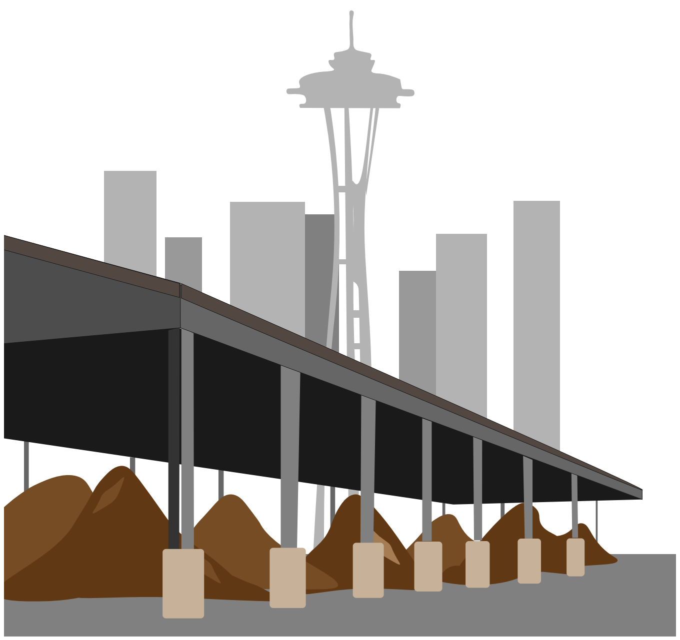
Photo: Karoline Thalhofer

Reducing contamination was the most frequently mentioned limitation to expanded municipal compost use. This is not surprising in that it is often mentioned as the primary concern for other compost uses, such as within agriculture. Reducing contamination at the compost production stage can drastically increase compost production costs, so there is often a focus on reducing contamination earlier on.

One way to do this is with materials standards, particularly related to service ware. An opinion expressed was that there needs to be a nationwide standardized coding scheme preferably with a user-friendly approach such as color coding. Manufacturers of these products sell to many states, so a nationwide standard is necessary from that perspective. However, there may be some growing pains in conforming state-mandated testing requirements with national material standards.

Another factor potentially affecting contamination, that was mentioned by respondents, is voluntary versus mandatory organic waste collection. While a possibly controversial opinion, it was argued that voluntary collection programs may have lower levels of contamination than mandatory programs that require households to separate organic waste from other waste. With time and resources, this question could be considered empirically. What is more certain is that there is a tradeoff between contamination and the amount of organic waste diverted from landfills. If mandatory programs divert more from landfills but also increase contamination in compost, there may be a difficult tradeoff to make between the two that considers a wide range of costs and benefits. It is almost certainly a decision that many municipalities will make in the future. Spokane is an example of a voluntary program. It currently has about 36,000 subscribers, each paying a cost of $18.31/month. Drop off is also an option. Compost processing is done by a third party and generates about 20,000 tons of compost per year. Spokane does not currently have a buyback program with the compost processor.

Inconsistency in municipal compost demand was highlighted as a challenge to formalizing municipal compost procurement particularly for small- and medium-sized cities. Their perspective is that compostuse is tied to specific capital projects, like parks and roads, that are inconsistent over time. This contrasts with the timing of organic waste generation, which varies in predictable ways over the course of the year, and therefore with compost production cycles. One option mentioned was the construction of larger storage facilities that would allow for carryover from one year to the next. Another possibility is for agreements among multiple towns and cities that are near each other.



Funding was also cited as a major limitation for many municipalities. Needs for funding ranged from salaries for workers to larger facilities for storage or compost curing. One perspective on funding is that demand for compost is not yet robust enough for these programs to be self-sustaining. However, it is important to recognize that this need not be a requirement. Diversion of organic waste from landfills and expanded use of compost creates a wide range of benefits that are not easily monetized, that therefore may justify public funding. For example, reduced GHG emissions from landfills are not reflected in the price paid by a compost user. However, there may be difficult decisions to make in program design that do affect the level of public funding needed to sustain programs. Compost supply and demand is very local because of feedstocks and costs of transportation, so diverse approaches are needed.

Photo: Ansyvan stock.adobe.com

Key Messages for Legislature

Meeting the goals of HB 1799 will require improvements in administrative systems for tracking use and overcoming obstacles to using compost for various applications.

Most municipalities contacted had very little information readily available on their current and past compost use. Documenting use is likely to be less of a problem for large cities like Tacoma, Seattle, and Spokane. Smaller and medium-sized cities should consider the development of a common system that all can use. Although documenting quantities of compost used by towns, cities, and counties is perceived to require significant additional effort, overcoming this obstacle could lead to improved insights over time about what strategies are working most effectively to encourage local government compost use, and what barriers need to be addressed.

Most local governments do not purchase compost. Most of these entities are small and do not have parks or capital projects, while a few are in areas of the state where compost is not available nearby.

Contamination with non-compostable items in finished compost, was the most frequently mentioned obstacle to greater municipal use of compost.

City size is also an important consideration in overcoming obstacles to increased municipal compost use. For example, inconsistency in municipal compost demand is a significant issue for smaller cities but is likely to be less of a problem for large cities. For smaller cities, challenges in producing more compost (and in some cases use by the public) tend to limit higher governmental procurement.

REFERENCES

1. Georgiou, K., et al., Global stocks and capacity of mineral-associated soil organic carbon. Nature Communications, 2022. 13(1): p. 3797.
2. Guillaume, T., et al., Soil organic carbon saturation in cropland-grassland systems: Storage potential and soil quality. Geoderma, 2022. 406: p. 115529.
3. Prout, J.M., et al., Changes in organic carbon to clay ratios in different soils and land uses in England and Wales over time. Scientific Reports, 2022. 12(1): p. 5162.
4. Johannes, A., et al., Optimal organic carbon values for soil structure quality of arable soils. Does clay content matter? Geoderma, 2017. 302: p. 14-21.
5. Rosinger, C., et al., Benchmarking carbon sequestration potentials in arable soils by on-farm research on innovative pioneer farms. Plant and Soil, 2022.
6. Bauer, A. and A.L. Black, Quantification of the effect of soil organic matter content on soil productivity. Soil Science Society of America Journal, 1994. 58(1): p. 185-193.
7. Golchin, A., J. Baldock, and J. Oades, A model linking organic matter decomposition, chemistry, and aggregate dynamics. Soil processes and the carbon cycle. CRC Press, Boca Raton, 1997: p. 245-266.
8. Kononova, M., Soil Organic Matter: Its Nature, Its Role in Soil Formation and in Soil Fertility. Tradução TZ Nowakowski, GA Greenwood. 1961: Pergamon Press.
9. Nolan, C.J., C.B. Field, and K.J. Mach, Constraints and enablers for increasing carbon storage in the terrestrial biosphere. Nature Reviews Earth & Environment, 2021. 2(6): p. 436-446.
10. Bossio, D.A., et al., The role of soil carbon in natural climate solutions. Nature Sustainability, 2020. 3(5): p. 391-398.
11. Sharratt, B.S., et al., Soil Carbon Loss by Wind Erosion of Summer Fallow Fields in Washington's Dryland Wheat Region. Soil Science Society of America Journal, 2018. 82(6): p. 1551-1558.
12. Ecology, W.S.D.o., The state solid and hazardous waste plan: moving Washington beyond waste and toxics. 2021: Olympia, Washington. U.S.A.
13. Ecology, W.S.D.o., Washington Statewide Waste Characterization Study. 2021: Olympia, WA, U.S.A.
14. Brien, C.J. asremlPlus: augments ASReml-R in fitting mixed models and packages generally in exploring prediction differences. R package version 4.1-28. 2019 June 17, 2019]; Available from: https://cran.at.r-project.org/package=asremlPlus.
15. Butler, D.G., et al., Analysis of Mixed Models for S language environments: ASReml-R reference manual. 2009, DPI Publications: Brisbane.
16. Butler, D.G., et al., ASReml-R reference manual. The State of Queensland, Department of Primary Industries and Fisheries, Brisbane, 2009.
17. Parton, W.J., et al., Measuring and mitigating agricultural greenhouse gas production in the US Great Plains, 1870–2000. Proceedings of the National Academy of Sciences, 2015. 112(34): p. E4681-E4688.
18. Cogger, C.G., et al., Soil physical properties, nitrogen, and crop yield in organic vegetable production systems. Agronomy Journal, 2016. 108(3): p. 1142-1154.
19. Pritchett, K., A.C. Kennedy, and C.G. Cogger, Management effects on soil quality in organic vegetable systems in western Washington. Soil Science Society of America Journal, 2011. 75(2): p. 605-615.
20. Adewale, C., et al., Agricultural carbon footprint is farm specific: Case study of two organic farms. Journal of Cleaner Production, 2019. 229: p. 795-805.
21. Pereira, B.d.J., A.B. Cecílio Filho, and N. La Scala, Greenhouse gas emissions and carbon footprint of cucumber, tomato and lettuce production using two cropping systems. Journal of Cleaner Production, 2021. 282: p. 124517.
22. R Core Team, R: A Language and Environment for Statistical Computing. 2020, R Foundation for Statistical Computing: Vienna, Austria.
23. Hills, K., et al., Differentiating the value and cost of compost across likely farm use scenarios in Western Washington. A technical report completed as part of the Waste to Fuels Technology Partnership. 2019, Washington State University, Puyallup, WA, USA.

Photo: LifeisticAC- stock.adobe.com

Authors

Part 1: Kirsten Ball, Ian Burke, Doug Collins, Karen Hills, Chad Kruger, and Georgine Yorgey.

Part 2: Michael Brady, Ben Stone, and Emma Taylor.

Acknowledgements

For the Puyallup field trials, we thank Emma Rast for her assistance in field and laboratory analysis and Liz Myhre for technical assistance, and Craig Cogger and Andy Bary for their efforts to initiate and operate a long-term organic farming research experiment at WSU Puyallup from 2003-2016. These trials were funded by the Western Sustainable Agriculture Research and Education Program (project no. SW-03-040), the USDA NIFA Integrated Organic Program (project no. WNP07725), and the Agricultural Research Center at Washington State University (Hatch Project 0722).

For the Davenport field trials, we thank Rachel Zuger, Nicole Tautges, and Holly Lane. This project was funded by the USDA-NIFA Organic Research and Extension Initiative Program (project nos. 2014-38421-22002 and 2019-51300-30476) and the CAHNRS Office of Research at Washington State University (Hatch project 1017286).

For this report as a whole, we acknowledge the invaluable input from our external advisory committee: Alison Halpern, Washington State Conservation Commission; Emily Coleman and Alexandra Blum, King County; Kate Kurtz, Seattle Public Utilities; Danielle Gelardi, Washington State Department of Agriculture; and Chery Sullivan, Washington State Department of Ecology.

Likewise, we acknowledge the critical input from our Advisory Committee: Jim Amonette, Center for Sustaining Agriculture & Natural Resources (joint appointee with Pacific Northwest National Laboratory); Chris Benedict, Center for Sustaining Agriculture & Natural Resources, Washington Soil Health Initiative and WSU Extension; Deirdre Griffin LaHue, Department of Crops and Soils; and Kirti Rajagopalan, Department of Biological Systems Engineering.

We thank Katie Doonan, for assistance with graphics and report layout.

Suggested Citation

Ball, K.R., M.P. Brady, I.C. Burke, D.P. Collins, K.M. Hills, C.E. Kruger, B. Stone, E.L. Taylor, and G.G. Yorgey. Evaluating Compost Application for Soil Carbon Sequestration on Agricultural Land and Compost Buy-Back Programs in Washington State. Report to the Washington State Legislature. Center for Sustaining Agriculture & Natural Resources, Washington State University, Wenatchee, WA

Cover Photo Attribution

Organic compost pile. William - stock.adobe.com

WASHINGTON STATE UNIVERSITY
Center for Sustaining Agriculture and Natural Resources